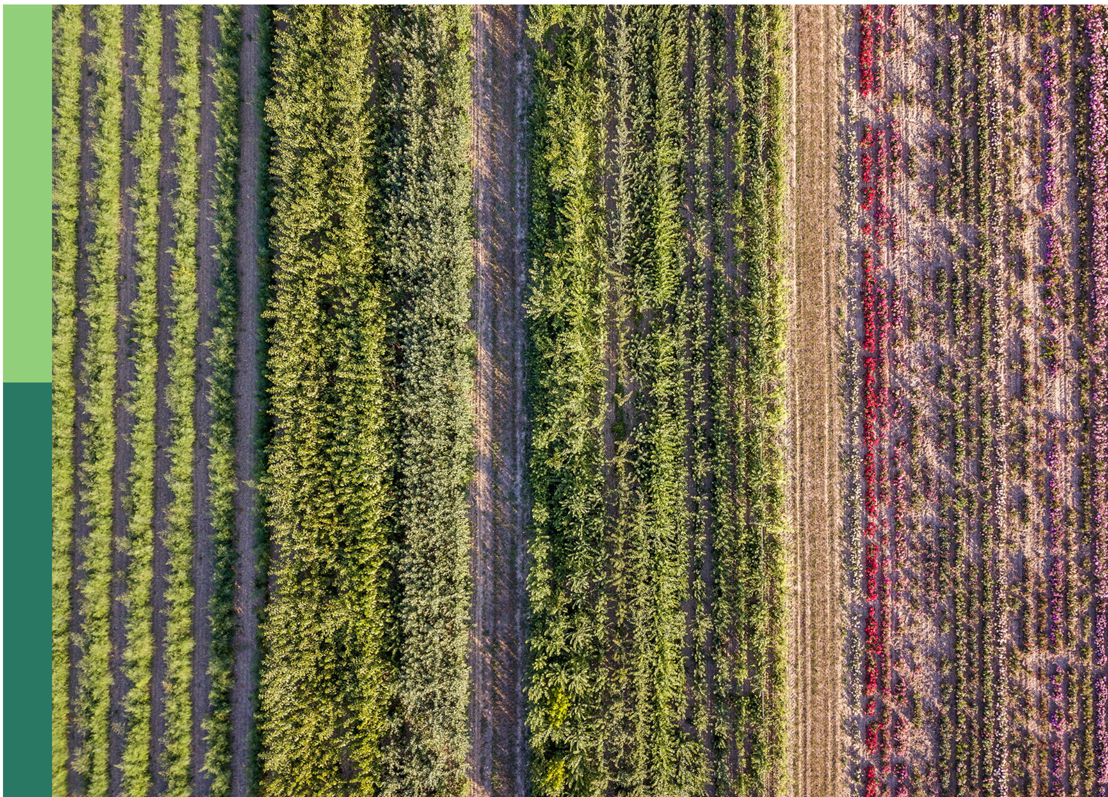
frontiers | Research Topics

# Socio-economic evaluation of cropping systems for smallholder farmers – challenges and options

**Edited by**
Subhasis Mandal, Sendhil R. and Rupak Goswami

**Published in**
Frontiers in Sustainable Food Systems



ISSN 1664-8714
ISBN 978-2-8325-3938-5
DOI 10.3389/978-2-8325-3938-5

## About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

## Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

## Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

## What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

# Socio-economic evaluation of cropping systems for smallholder farmers – challenges and options

**Topic editors**
Subhasis Mandal — National Dairy Research Institute (ICAR), India
Sendhil R. — Pondicherry University, India
Rupak Goswami — Ramakrishna Mission Vivekananda Educational and Research Institute, India

**Citation**
Mandal, S., Sendhil, R., Goswami, R., eds. (2023). *Socio-economic evaluation of cropping systems for smallholder farmers – challenges and options*.
Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-3938-5

# Table of contents

frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 01 November 2023
DOI 10.3389/fsufs.2023.1310448

OPEN ACCESS

EDITED AND REVIEWED BY
Ole Mertz,
University of Copenhagen, Denmark

*CORRESPONDENCE
Subhasis Mandal
✉ subhasis2006@gmail.com

RECEIVED 09 October 2023
ACCEPTED 19 October 2023
PUBLISHED 01 November 2023

CITATION
Mandal S, Sendhil R and Goswami R (2023) Editorial: Socio-economic evaluation of cropping systems for smallholder farmers – challenges and options. *Front. Sustain. Food Syst.* 7:1310448. doi: 10.3389/fsufs.2023.1310448

# Editorial: Socio-economic evaluation of cropping systems for smallholder farmers – challenges and options

Subhasis Mandal[1]*, R. Sendhil[2] and Rupak Goswami[3]

[1]National Dairy Research Institute (ICAR), Karnal, India, [2]Department of Economics, School of Management, Pondicherry University, Puducherry, India, [3]Ramakrishna Mission Vivekananda Educational and Research Institute, Kolkata, West Bengal, India

KEYWORDS

**cropping systems, economic impact, agricultural policy, natural farming, crop diversification, smallholder farmers, sustainable agriculture, SDG**

Editorial on the Research Topic
Socio-economic evaluation of cropping systems for smallholder farmers – challenges and options

Sustainable farming practices for smallholder farmers have taken center stage due to significant transformation in the agricultural food supply systems, shifting paradigms of understanding the sustainability of agricultural systems, and mounting concerns about food and nutrition security. Smallholders across the globe contribute significantly to global food production and are likely to continue in the future. The performances of smallholders' cropping systems directly impact the achievement of Sustainable Development Goals (2030) *viz.*, No Poverty (SDG 1), Zero Hunger (SDG 2), and Good Health and Wellbeing (SDG 3). Given the rising input costs without an equivalent increase in the output prices coupled with its instability, challenges the economic viability of smallholder agri-food systems. Cropping system intensification (CSI) could be one of the ways to make such production systems remunerative, and smallholder agricultural systems need to evolve around sustainable intensification principles to enhance agricultural productivity without conceding environmental and social externalities.

The collection of articles on the Research Topic examined the multifaceted realm of cropping systems relating to achieving SDGs, climate change challenges and adaptation, crop diversification, cooperative and land entitlement, crop-livestock integration, natural farming, coastal and mariculture, and COVID's impact on such production systems. Researches, mostly based on empirical evidence, quantified the contribution and constraints of smallholder farmers' agri-food production systems. As we explore the challenges and options surrounding economic evaluation, we take stock of innovative solutions that enhance smallholders' livelihoods and contribute to the broader goal of agricultural sustainability. This curated Research Topic of papers documents practices, and offers insights and policy inferences essential for addressing the issues that smallholders face to foster resilient and equitable agricultural value-chains. Although our current Research Topic focuses on economic evaluation, we are critically aware of the transforming contour of related literature that broadens the scope of economic evaluation of cropping systems to social and ecological issues within the overarching context of climate change adaptations. Our bibliometric analysis draws on the scholarly literature search facility of The Lens (https://www.lens.org/) using

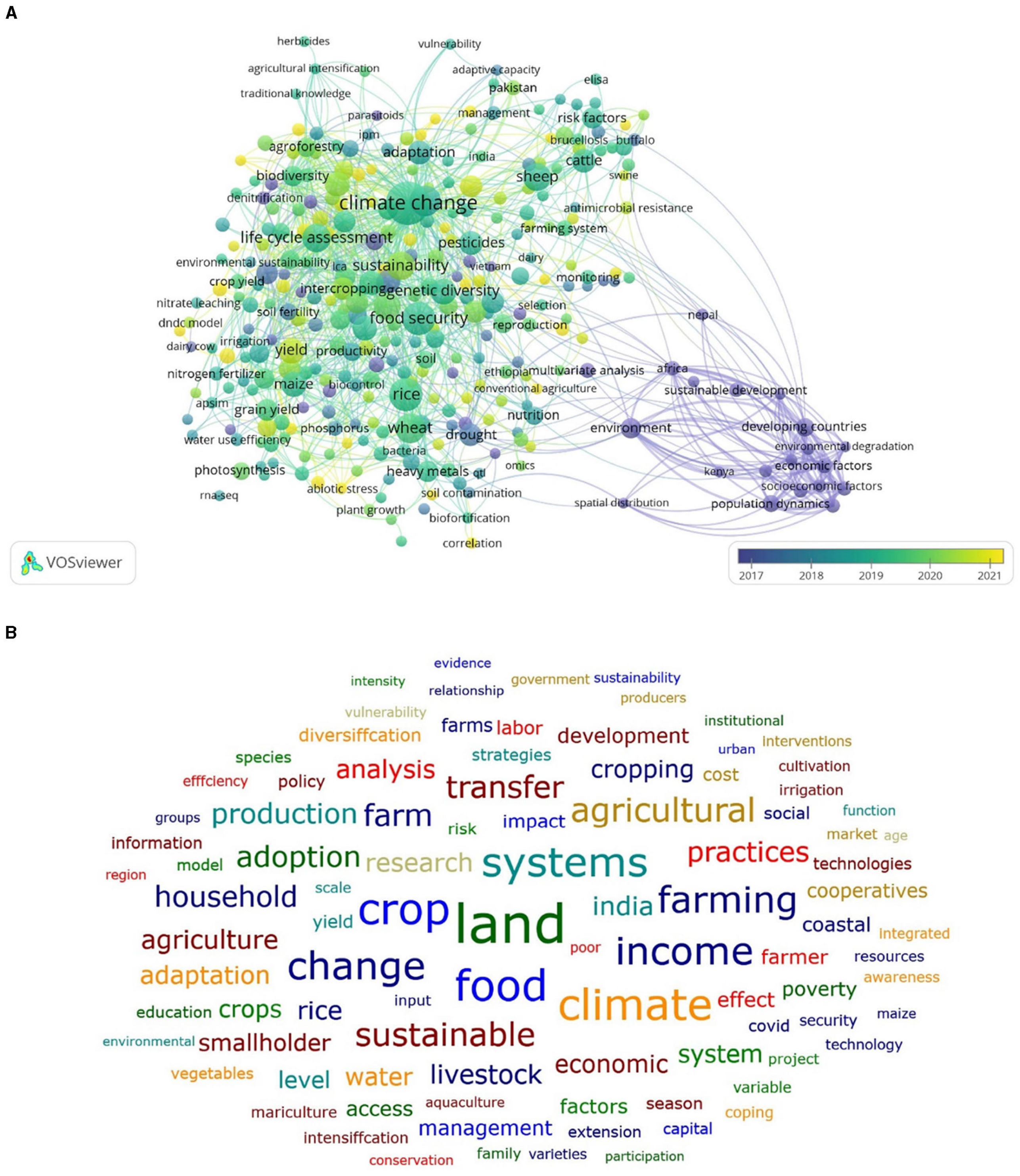


FIGURE 1

**(A)** Bibliometric analysis covering more than 30,000 articles shows the trend of cropping systems assessment toward multicriteria undertakings within the realm of climate change; **(B)** articles in the current Research Topic align with the existing literature with an explicit focus on systems thinking and institutional arrangements.

an iteratively formulated search string. We included journal articles from the search results and exported the bibliographic citation file to VOSviewer software to generate visualizations of bibliometric networks (Figure 1A). The co-occurrence network of keywords suggests, the evaluation of cropping systems has recently moved from economic analysis to sustainability parameters such as food security, genetic diversity, environmental externalities in the context of climate change. We analyzed the articles in the Research Topic by using ATLAS.ti software to generate a wordle featuring words that appeared more frequently in the current volume. We find the papers of this issue aligning well with this transforming scholarship (Figure 1A) and also demonstrate an explicit preoccupation with system thinking and institutional arrangements (Figure 1B).

A perspective paper by Willow and Veromann highlighted that RNAi-based technology can be a good option for managing pests in small farms if infrastructure supports are provided. RNAi technology holds a promising solution for controlling outbreaks of pests in various cropping systems. Promoting such technology may also require credible educational support from the scientific community and practitioners to overcome the "high-risk" apprehension of the smallholders.

A diversified cropping pattern with the inclusion of vegetables could be a prospective option for smallholder farmers to generate cash income and reduce the risks of crop failure due to irregular rainfall (Manickam et al.). The incorporation of vegetables in the cropping systems could also increase nutrition intake of the poverty-stricken farm-households, which might otherwise remain unaffordable to them. In a similar vein, Mandal et al. in their study on CSI in coastal agricultural systems reported a substantial increase in smallholder farmers' income achieved by reducing the yield gap. Successful CSI through active collaboration with farmers helped them acquire new knowledge of cultivation practices and expedited the adoption of remunerative cropping systems. Collaboration between researchers and farmers helped in the identification of appropriate cropping system interventions for the farmers.

The impact of climate change is overarching in agri-food systems irrespective of farm sizes, and its effect on food production systems poses an imminent threat to human nutrition, health, and future development. Evidence from a study showed that adoption of practices such as improved varieties, irrigation practices, direct seeded rice, integrated pest management, and adjustment in crop calendar could enhance the production capacities of the farmers (Upendram et al.). Increased access to information and technical knowledge of adaptation practices and the adequacy of financial resources can facilitate the adoption of climate adaptation measures by small farms. Another study highlighted the increasing role of institutions, both government and private, is essential in the future to safeguard the interests of farmers by offering research outputs, technology interventions, and policy support (Kumar et al.). Also, the use of ICTs and artificial intelligence can be made an integral part of climate change mitigation and adaptation strategies in agriculture. To achieve higher resilience in agriculture, it is important to understand how smallholder farmers perceive and integrate climate-smart technologies into their farming practices (Mallappa and Pathak). Socio-economic backgrounds of the farmers, such as education, income, exposure to mass media, linkages with extension programmes, innovativeness, and risk orientation, are determinants for adopting climate-smart agricultural technologies. Besides, timely supply of inputs and continuous engagement with other stakeholders, including successful farmers, are key to the adoption of climate-smart agricultural practices.

The concept of natural farming embodied with chemical-free agricultural production system based on Indian traditional knowledge blended with modern understanding of ecology, resource recycling and on-farm resource optimization. The integration of locally available resources and reduction of external input uses can be a viable proposition, particularly for farmers operating in low-input and low-cost conditions (Laishram et al.). The study indicated that natural farming practices can be successful when promoted with vegetable-based cropping systems and multiple crops involving legumes. Although there was initially a drop in crop yields, but the net return was significantly higher compared to conventional practices, mainly due to cost savings on account of no use of fertilizer and pesticides. However, natural farming is highly labor-intensive and deserves a better market price (premium price) to make the practices remunerative for the farmers.

The economic impact of COVID-19 on income and livelihoods covering rural and urban households was assessed by Kang et al.. Their study indicated that the economic impact of COVID-19 was greater in urban areas than in rural areas, and the urban conditions improved before the rural areas. It also highlighted the potential impact pathways of COVID-19, from a household economic downturn to limited food spending, poor food consumption, and increased use of short-term coping mechanisms.

Xie et al. evaluate the relationship between rural land titling (RLT) and rural land transactions and examine whether RLT impacts the efficient resource allocation. Their analysis shows that RLT promotes rural land transactions weakly, and facilitates rural land transfer-out only, having no effect on rural land transfer-in. They suggest simplifying agricultural land property rights may not lead to a sustainable rural agricultural production system; rather, policies need to align with local communities' interests, considering the traditional cultures and social needs. Another study by Liu et al. evaluated the relationship between the promotion of rural cooperatives and its impact on poverty and vulnerability. Participation in rural cooperatives significantly reduces poverty vulnerability among farm households with higher human capital and income compared to households with lower human capital and income. They suggest policies that encourage farmers to join or start cooperatives and support cooperative development to reduce poverty among smallholder farmers.

Dhehibi et al. moved beyond the crop sector and assessed the synergies between crop and livestock under conservation agriculture with a potential advantage for sustainable intensification in smallholder systems. They observe higher technical inefficiencies in integrated crop-livestock systems, but economic diversification provides a productivity gain that buffers against climate-induced uncertainties.

Parappurathu et al. assessed the long-term suitability of selected mariculture enterprises with a special focus on small-scale mariculture systems. They highlighted potential enterprises for future scale-up of mariculture, such as open sea cage farming, coastal water cage farming, seaweed farming, and integrated multi-trophic aquaculture. The authors found selected enterprises to be technically and economically viable in general. However, certain gaps were evident in terms of key sustainability indicators, such as legitimate access to water bodies, quality of seed and feed, access to institutional credit and market, fair marketing practices, optimal stocking density, mechanization, renewable energy use, adoption of environmental-friendly practices, farm surveillance, crew safety, and social protection.

This Research Topic places us at the intersection of knowledge and action. Insights shared by the contributed papers underscore the importance of recognizing the unique dynamics that smallholder farmers face across countries. It is evident that smallholders' success is vital for their own wellbeing, ensuring global food security and sustainable agriculture. As we move forward, it is imperative that policymakers, researchers, and stakeholders collaborate to address these challenges and embrace the available options. By adopting holistic approaches, supporting innovations, and implementing relevant policies, smallholders can be empowered to thrive economically while safeguarding the planet's scarce resources and inspire them to work toward a more equitable and sustainable future for agriculture.

## Author contributions

SM: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. RS: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. RG: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

## Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

## Acknowledgments

We would like to thank profusely and acknowledge the contributions made by all the authors and reviewers for completing the Research Topic. We would like to express our sincere thanks to all associated from Frontiers from the very beginning, conceptualizing to completing the Research Topics.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

frontiers | Frontiers in Sustainable Food Systems

PERSPECTIVE
published: 25 April 2022
doi: 10.3389/fsufs.2022.868922

# Integrating RNAi Technology in Smallholder Farming: Accelerating Sustainable Development Goals

*Jonathan Willow*[1,2]* *and Eve Veromann*[1]

*[1] Chair of Plant Health, Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Tartu, Estonia, [2] Department of Plants and Crops, Laboratory of Agrozoology, Faculty of Bioscience Engineering, Ghent University, Ghent, Belgium*

Approximately 84% of farms globally are <2 hectares; these and other smallholder farms collectively produce over one third of humanity's food. However, smallholder farms, particularly in developing countries, encounter difficulties in both production and profits due to their vulnerabilities. Sustainable intensification—increasing crop yield without significantly greater resource use—must be globally adopted in smallholder farming to achieve various Sustainable Development Goals (SDGs) endorsed by the United Nations (UN). While traditional techniques for conservation agriculture must be maintained and further promoted, new technologies will undoubtedly play a major role in achieving high yields in a sustainable and environmentally safe manner. RNA interference (RNAi) technology, particularly the use of transgenic RNAi cultivars and/or sprayable double-stranded RNA (dsRNA) pesticides, could accelerate progress in reaching these goals due to dsRNA's nucleotide sequence-specific mode of action against eukaryotic and viral pests. This sequence-specificity allows silencing of specific genetic targets in focal pest species of interest, potentially resulting in negligible effects on non-target organisms inhabiting the agroecosystem. It is our perspective that recent progress in RNAi technology, together with the UN's endorsement of SDGs that promote support in- and for developing countries, should facilitate an integrated approach to sustainable intensification of smallholder farms, whereby RNAi technology is used in combination with traditional techniques for sustainable intensification. However, the development of such approaches in developing countries will require developed countries to adhere to currently-defined socioeconomic SDGs.

**Keywords: sustainable intensification, conservation agriculture, dsRNA, spray-induced gene silencing, transgenic, pesticide, integrated pest management, developing countries**

***Edited by:***
*Subhasis Mandal,*
*Central Soil Salinity Research Institute (ICAR), India*

***Reviewed by:***
*Durgesh K. Jaiswal,*
*Savitribai Phule Pune University, India*

****Correspondence:***
*Jonathan Willow*
*jonathan@emu.ee*

***Specialty section:***
*This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems*

***Received:*** *03 February 2022*
***Accepted:*** *30 March 2022*
***Published:*** *25 April 2022*

***Citation:***
*Willow J and Veromann E (2022) Integrating RNAi Technology in Smallholder Farming: Accelerating Sustainable Development Goals. Front. Sustain. Food Syst. 6:868922. doi: 10.3389/fsufs.2022.868922*

## CHALLENGES TO SUSTAINABLE FOOD PRODUCTION, AND CONTEMPORARY ROLE OF TRADITIONAL PRINCIPLES, IN SMALLHOLDER FARMS

As both arable land and water resources are becoming less abundant relative to dependent human populations, the United Nations (UN) has ambitiously set to achieve various Sustainable Development Goals (SDGs) by 2030 (United Nations, 2022). Each goal is relevant to a broader action plan for people, planet and prosperity; SDG 2—End hunger, achieve food security and improved nutrition, and promote sustainable agriculture—fully relates to sustainable food production. This goal attempts to mitigate the negative effects of resource scarcity on hunger, especially in developing countries where poverty and hunger present major problems within these communities.

Sustainable farming systems must be in place globally to counteract and prevent hunger in local, regional and foreign human populations. Of the ∼570 million farms globally, most are small, 84% being under two hectares (Lowder et al., 2016). Smallholder farms represent a critical focus for achieving sustainable food production, given the global distribution of smallholder farms and their contribution to producing over a third of the world's food (Lowder et al., 2021). Furthermore, a recent evidence review and meta-analysis showed that smaller farms have, on average, higher yields and greater crop- and non-crop biodiversity than larger farms (Ricciardi et al., 2021).

Smallholder farms include some of the most vulnerable crop production systems, as they are often less- or insufficiently resourced for preventing crop damage (e.g., due to crop pests, farmland erosion, climate hazards). In addition, smallholder farms often have a more difficult time making profits from their labor, due to relatively small quantities of food produced, lack of social protection, dependency on less farm hands, and their disadvantage in supply chains. To provide for an exponentially growing human population, smallholder farming systems must undergo sustainable intensification, whereby crop yields are increased in a manner that minimizes environmental impacts without significantly greater expenditure of resources (e.g., water, land, labor costs). Traditional practices, together with newer technologies, have both been developed with the aim of aiding sustainable intensification in crop production; SDGs 1.4, 8.2, 9.4, and 9.5 (United Nations, 2022; **Table 1**) encourage greater adoption- and upgrades of technologies in developing countries. Indeed, sustainable intensification is likely to require a combination of both traditional- and biotechnological approaches to achieve the established SDGs.

Diversified cropping systems, as well as landscape heterogeneity, represent long-held approaches to sustainable food production. Such approaches for diversification aim to enhance sustainable production via promoting ecological diversity at both field- and landscape scales. Cropping systems such as inter-, under- and cover cropping, maintaining crop diversity, preserving and restoring natural and seminatural habitats, and implementation of diverse agroforestry practices can enhance both above- and belowground ecosystem services in smallholder farms, allowing reductions in external inputs, thereby promoting healthy viable agroecosystems; they can also benefit food- and nutrition security and encourage diverse diets, without reducing crop yields (Chai et al., 2021; Drinkwater et al., 2021; Jemal et al., 2021; Priyadarshana et al., 2021; Rodriguez et al., 2021). However, diversified cropping systems continue to raise both economic and social challenges that must be overcome, and smallholder farmers understand that crop diversification is not a standalone sustainable solution (Rodriguez et al., 2021). Furthermore, ecosystem services are not explicitly considered to be key factors for achieving SDGs in developing countries (Knight, 2021). Some principles of conservation agriculture may even limit crop productivity. For example, in an analysis of field trials across 48 crops and 68 countries, yield declines with an overall mean of 10% were observed when no-tillage was applied in the absence of other sustainable intensification practices (Pittelkow et al., 2015). Thus, traditional techniques for sustainable intensification should not be implemented alone, but rather alongside other field- and landscape scale measures.

**TABLE 1 |** Sustainable Development Goal (SDG) targets, endorsed by the United Nations (UN), relevant to adopting RNAi crop technology in developing countries.

| | |
|---|---|
| **Target 1.4.** | "By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance" |
| **Target 8.2.** | "Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labor-intensive sectors" |
| **Target 9.4.** | "By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities" |
| **Target 9.5.** | "Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending" |

*Descriptions of UN SDG targets to be achieved by 2030 are taken from the UN's Sustainable Development website (https://sdgs.un.org).*

Given the variability of environmental and socioeconomic conditions surrounding smallholder farming, sustainable intensification interventions must be adapted to local contexts (Reich et al., 2021). Furthermore, traditional techniques for sustainable resource management (e.g., intercropping, cover cropping, crop rotation, organic farming, agroforestry) should be applied using advanced technologies for efficient use of resources (Imoro et al., 2021). Indeed, while building upon the knowledge of indigenous communities is expected to be crucial for reaching SDGs (United Nations Environment Programme Food Agriculture Organization of the United Nations, 2020), the integration of new technologies can be pivotal in reaching these goals. While smallholder farmers may view new biotechnological applications as high-risk, the push to globally achieve SDGs requires that we explore the benefits of an interdisciplinary path to reach these goals. The current momentum in technological development, especially with regard to crop protection biotechnologies, also allows the development and assessment of more target-specific pesticides that potentially provide the most ecologically sustainable way to control crop pests.

## PROSPECTIVE ROLE OF RNAi TECHNOLOGY IN SUSTAINABLE INTENSIFICATION

Crop pests represent a dynamic, highly unpredictable and often difficult-to-control problem for farmers globally, and cautious pesticide use has become an important pillar of integrated pest management (Barzman et al., 2015). Pesticides are considered irreplaceable to farmers in situations where natural biological control is inadequate in regulating pests of cash crops, which renders such farms vulnerable without the integration of pesticides. Here we consider a biosafe pesticide technology: the use of transgenic RNA interference (RNAi) cultivars and/or sprayed double-stranded RNA (dsRNA), representing approaches that have made significant progress in crop protection research and are currently under development by several biotechnology companies (Rank and Koch, 2021; Willow and Veromann, 2021). The attraction to the use of RNAi as a crop protection technology is due to dsRNA's nucleotide sequence-specific mode of action against eukaryotes and viruses. This specificity allows remarkably target-specific control of crop pests, via the evolutionarily conserved mechanism of RNAi (Rank and Koch, 2021), potentially leaving beneficial non-target organisms (e.g., crop pollinators, biological control agents, soil decomposers) unharmed. This is in stark contrast to the observed effects of non-RNA pesticide technology on non-target organisms (Sgolastra et al., 2018; Simon-Delso et al., 2018; Calvo-Agudo et al., 2019; Willow et al., 2019; Schulz et al., 2021). Thus, SDGs 3.9, 12.4, 14.1, 15.5, and 15.9 (United Nations, 2022; **Table 2**) may be better achieved through the use of RNAi pesticide technology, rather than conventional pesticides which currently dominate the market.

RNAi technology represents a promising solution for controlling outbreaks of pests in various cropping systems (Baum et al., 2007; Koch et al., 2016; Mitter et al., 2017; Cagliari et al., 2019; Worrall et al., 2019; Petek et al., 2020; Rank and Koch, 2021). Harnessing RNAi technology for crop protection holds great potential for compatibility, and perhaps synergy, with conservation biological control services in agroecosystems, as a result of dsRNA's nucleotide sequence-specific mode of action (potentially conferring no toxicity to non-target organisms). Furthermore, dsRNA can be used to prevent plant virus transmission/vectoring by crop pests (Bahrami Kamangar et al., 2019; Worrall et al., 2019), as well as target non-essential mechanisms, thereby reducing pest population fitness while maintaining pest presence for specialized biological control agents (e.g., specialist predators, parasitoids) to sustain their own populations (Willow et al., 2021b). Rapid degradation of dsRNA in soils and waterbodies (Parker et al., 2019; Bachman et al., 2020) also presents important benefits over other types of pesticide molecules. However, as both dsRNA uptake and RNAi efficiency can vary between- and within taxa (Wytinck et al., 2020; Willow and Veromann, 2021), potentially necessitating the use of nanoparticles as co-formulants (Wytinck et al., 2020), the environmental fate of sprayed dsRNA must be examined under various formulation scenarios.

Both dsRNA production and transgenic biotechnologies have steadily increased in cost-efficiency over recent years. For example, with the advent of large-scale cell-free dsRNA production, the cost of dsRNA has dropped to <\$0.50 per gram (Rank and Koch, 2021). Since exogenously-applied (sprayed) dsRNA can be specifically designed to base-pair with endogenous messenger RNA (mRNA) that codes for a specific gene, this enables a multitude of molecular targets in any eukaryotic or viral pest with available transcriptome sequence information (necessary for designing a template for dsRNA synthesis). While this information is not currently available for most agricultural pests, current costs of obtaining whole-sequence information are no longer considered prohibitive, and promising initiatives are underway to mitigate this knowledge gap (Lewin et al., 2018; The Earth BioGenome Project, 2018; i5k, 2022).

Both RNAi cultivars and dsRNA sprays present certain advantages over each other. RNAi cultivars constantly produce the target-specific dsRNA in the plant's tissues, allowing the target pest to be constantly exposed to the pesticide, as long as the pest feeds on the transgenic crop. In some instances, chronic feeding on dsRNA can significantly enhance RNAi efficacy, compared to short-term feeding on dsRNA (Willow et al., 2021a). Thus, transgenic approaches to RNAi-based pest management may be necessary in many cases, supporting the use of RNAi cultivars over dsRNA sprays. On the other hand, dsRNA sprays can be altered (e.g., co-formulants, target gene) for adaptive management, and in cases of pest polyphagy, multiple crop species can be treated simultaneously to target the same organism, reducing the pest's ability to successfully take refuge on its secondary or tertiary host plant. Furthermore, dsRNA, when sprayed, is less persistent in the environment compared to that for RNAi cultivars (which constantly produce the target-specific dsRNA in the plant's tissues throughout the growing period); this reduced persistency tightens the period of potential exposure to dsRNA, lessening the chance of resistance development in target organisms, resistance development being a potential hurdle for RNAi implementation (Khajuria et al., 2018; Mishra et al., 2021). Finally, there is the possibility of efficient RNAi-based control via topical contact to sprayed dsRNA; this has been observed in aphids (Niu et al., 2019; Zheng et al., 2019; Yan et al., 2020), and is likely to be an effective method of control for additional

**TABLE 2 |** Sustainable Development Goal (SDG) targets, endorsed by the United Nations (UN), that may be better achieved through the use of RNAi crop technology, rather than conventional pesticides.

**Target 3.9.** "By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination"

**Target 12.4.** "By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment"

**Target 14.1.** "By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution"

**Target 15.5.** "Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species"

**Target 15.9.** "By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts"

*Descriptions of UN SDG targets to be achieved by 2030 are taken from the UN's Sustainable Development website (https://sdgs.un.org).*

insect pests, even though oral consumption of treated plant parts is the typical aim when spraying dsRNA for management of insect pests.

## INTEGRATING RNAi-BASED MANAGEMENT IN SMALLHOLDER FARMS

Whether considering traditional techniques for sustainable intensification, the use of new sustainable technologies, or a combination of both approaches, social and financial constraints to implementing RNAi are evident, especially in the context of smallholder farmers in developing countries. However, with the rapidly decreasing costs of both dsRNA production and transgenic biotechnologies, together with the increasing number of agriculturally relevant pest species with available genetic sequence information, the prospect of integrating these techniques to work toward sustainable resource management in smallholder farming systems is becoming increasingly realistic. Indeed, RNAi techniques have already been introduced into smallholder farming systems, with great success. For example, in 1998, the U.S. government allowed about 200 smallholder papaya farmers to begin planting a papaya ringspot virus (PRSV)-resistant cultivar, as PRSV had resulted in nearly 40% production loss. This RNAi cultivar, commercialized as Rainbow papaya, produced immediate positive results, not only halting the rapid decline of Hawaii's papaya industry, but returning production to levels similar to before PRSV invasion. Today this RNAi-based papaya dominates the Hawaiian papaya market (Kuo and Falk, 2020). More recently, in 2021, the Kenyan National Biosafety Authority has approved the environmental release of an RNAi cassava cultivar resistant to cassava brown steak virus (CBSV) and Ugandan cassava brown streak virus (UCBSV), both of which result in cassava brown streak disease (CBSD). This cultivar, known as 4046 cassava, shows a positive food- and feed safety profile compared to its non-transgenic parental cultivar (Wagaba et al., 2021). National performance trials currently being conducted are optimistic, and this cultivar is expected to soon be available to Kenyan cassava farmers (Cassava Plus, 2021). RNAi-based control of such viral diseases enhances sustainable intensification not only by increasing crop yields, but potentially also by reducing or eliminating the need to use insecticidal interventions against crop disease vectors (e.g., whiteflies, in the case of both CBSV and UCBSV). Using both tobacco and cowpea plants, Worrall et al. (2019) recently demonstrated the disruption of aphid-mediated virus transmission between plants, via exogenous application of dsRNA targeting bean common mosaic virus. Together these case studies suggest that both transgenic and dsRNA spray approaches can be mobilized to protect crops from viral diseases and potentially reduce the need to directly manage disease vectors.

It is paramount that progress in crop protection biotechnology does not exclude smallholder farmers in developing countries. This would require dependable socioeconomic support from local and foreign stakeholders and mid- or downstream sectors of food supply chains. It may also require dependable educational support from the scientific community and relevant expert practitioners, given the potential for smallholder farmers to view RNAi crop biotechnology as high-risk. Thus, financial support/investments and transfer of knowledge are both crucial to allow smallholder farmers to integrate sequence-specific biosafe pesticide technology into pest management strategies. Such aims can be facilitated by local and foreign adherence to defined targets in SDGs 1, 2, 4, 7, 8, 9, 10, 11, 12, 13, 15, and 17 (United Nations, 2022), which should be expected to be fully endorsed, in practice, by all able UN member states; the transfer of support from developed- to developing countries is particularly relevant here. Furthermore, the integration of new and traditional crop protection techniques are likely to facilitate a beneficial two-way transfer of knowledge regarding the use of sustainable intensification techniques.

It is our perspective that RNAi technology could be of great value to sustainable intensification of smallholder farms, including in developing countries, where there is currently the least infrastructure in place for implementing this technology. It must also be considered that achieving SDGs in agricultural and ecological sustainability innately requires adherence to socioeconomic SDGs designed to provide support for smallholder farmers in developing countries. Given the potential for ecologically sustainable crop protection via the use of RNAi technology, it remains vital to fill in the existing gaps regarding: (1) ensuring smallholder farmers satisfactory support; (2) obtaining transcriptome sequences of important crop pests globally; and (3) determining methods for cost-effective RNAi applications in pest taxa for which RNAi-based management is considered a possible solution.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

JW conceived the manuscript and wrote the original draft. All authors made comments/suggests toward revising the original draft, and approved the final version of the manuscript.

## FUNDING

This work was funded by the Personal Research Funding project No. PRG1056 of the Estonian Research Council.

## ACKNOWLEDGMENTS

The authors acknowledge Ana Isabel Silva, as well as our reviewer and editor, for providing comments and suggestions that helped to improve this manuscript.

## REFERENCES

Bachman, P., Fischer, J., Song, Z., Urbanczyk-Wochniak, E., and Watson, G. (2020). Environmental fate and dissipation of applied dsRNA in soil, aquatic systems, and plants. *Front. Plant Sci.* 11, 21. doi: 10.3389/fpls.2020.00021

Bahrami Kamangar, S., Christiaens, O., Taning, C. N. T., De Jonghe, K., and Smagghe, G. (2019). The cuticle protein MPCP2 is involved in Potato virus Y transmission in the green peach aphid *Myzus persicae*. *J. Plant Dis. Prot.* 126, 351–357. doi: 10.1007/s41348-019-00232-w

Barzman, M., Bàrberi, P., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., et al. (2015). Eight principles of integrated pest management. *Agron. Sustain. Dev.* 35, 1199–1215. doi: 10.1007/s13593-015-0327-9

Baum, J. A., Bogaert, T., Clinton, W., Heck, G. R., Feldmann, P., Ilagan, O., et al. (2007). Control of coleopteran insect pests through RNA interference. *Nat. Biotechnol.* 25, 1322–1326. doi: 10.1038/nbt1359

Cagliari, D., Dias, N. P., Galdeano, D. M., dos Santos, E. Á., Smagghe, G., and Zotti, M. J. (2019). Management of pest insects and plant diseases by non-transformative RNAi. *Front. Plant Sci.* 10, 1319. doi: 10.3389/fpls.2019.01319

Calvo-Agudo, M., González-Cabrera, J., Picó, Y., Calatayud-Vernich, P., Urbaneja, A., Dicke, M., et al. (2019). Neonicotinoids in excretion product of phloem-feeding insects kill beneficial insects. *Proc. Natl Acad. Sci. U. S. A.* 116, 16817–16822. doi: 10.1073/pnas.1904298116

Cassava Plus. (2021). *GMO Cassava*. Available online at: https://cassavaplus.org/news/kenya-citizentv-gmo-cassava (accessed March 20, 2022).

Chai, Q., Nemecek, T., Liang, C., Zhao, C., Yu, A., Coulter, J. A., et al. (2021). Integrated farming with intercropping increases food production while reducing environmental footprint. *Proc. Natl Acad. Sci. U. S. A.* 118, e2106382118. doi: 10.1073/pnas.2106382118

Drinkwater, L. E., Midega, C. A. O., Awuor, R., Nyagol, D., and Khan, Z. R. (2021). Perennial legume intercrops provide multiple belowground ecosystem services in smallholder farming systems. *Agric. Ecosyst. Environ.* 320, 107566. doi: 10.1016/j.agee.2021.107566

i5k (2022). *i5k: Sequencing Five Thousand Arthropod Genomes*. i5K. Available online at: http://i5k.github.io/ (accessed January 10, 2022).

Imoro, Z. A., Imoro, A. Z., Duwiejuah, A. B., and Abukari, A. (2021). Harnessing indigenous technologies for sustainable management of land, water, and food resources amidst climate change. *Front. Sustain. Food Syst.* 5, 282. doi: 10.3389/fsufs.2021.691603

Jemal, O. M., Callo-Concha, D., and van Noordwijk, M. (2021). Coffee agroforestry and the food and nutrition security of small farmers of south-western Ethiopia. *Front. Sustain. Food Syst.* 5, 293. doi: 10.3389/fsufs.2021.608868

Khajuria, C., Ivashuta, S., Wiggins, E., Flagel, L., Moar, W., Pleau, M., et al. (2018). Development and characterization of the first dsRNA-resistant insect population from western corn rootworm, *Diabrotica virgifera* LeConte. *PLoS ONE* 13, e0197059. doi: 10.1371/journal.pone.0197059

Knight, J. (2021). Environmental services: a new approach toward addressing sustainable development goals in sub-Saharan Africa. *Front. Sustain. Food Syst.* 5, 241. doi: 10.3389/fsufs.2021.687863

Koch, A., Biedenkopf, D., Furch, A., Weber, L., Rossbach, O., Abdellatef, E., et al. (2016). An RNAi-based control of *Fusarium graminearum* infections through spraying of long dsRNAs involves a plant passage and is controlled by the fungal silencing machinery. *PLoS Pathog.* 12, e1005901. doi: 10.1371/journal.ppat.1005901

Kuo, Y.-W., and Falk, B. W. (2020). RNA interference approaches for plant disease control. *Biotechniques* 69, 469–477. doi: 10.2144/btn-2020-0098

Lewin, H. A., Robinson, G. E., Kress, W. J., Baker, W. J., Coddington, J., Crandall, K. A., et al. (2018). Earth BioGenome Project: sequencing life for the future of life. *Proc. Natl Acad. Sci. U. S. A.* 115, 4325–4333. doi: 10.1073/pnas.1720115115

Lowder, S. K., Sánchez, M. V., and Bertini, R. (2021). Which farms feed the world and has farmland become more concentrated? *World Dev.* 142, 105455. doi: 10.1016/j.worlddev.2021.105455

Lowder, S. K., Skoet, J., and Raney, T. (2016). The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Dev.* 87, 16–29. doi: 10.1016/j.worlddev.2015.10.041

Mishra, S., Dee, J., Moar, W., Dufner-Beattie, J., Baum, J., Dias, N. P., et al. (2021). Selection for high levels of resistance to double-stranded RNA (dsRNA) in Colorado potato beetle (*Leptinotarsa decemlineata* Say) using non-transgenic foliar delivery. *Sci Rep.* 11, 6523. doi: 10.1038/s41598-021-85876-1

Mitter, N., Worrall, E. A., Robinson, K. E., Li, P., Jain, R. G., Taochy, C., et al. (2017). Clay nanosheets for topical delivery of RNAi for sustained protection against plant viruses. *Nat. Plants* 3, 1–10. doi: 10.1038/nplants.2016.207

Niu, J., Yang, W.-J., Tian, Y., Fan, J.-Y., Ye, C., Shang, F., et al. (2019). Topical dsRNA delivery induces gene silencing and mortality in the pea aphid. *Pest Manag. Sci.* 75, 2873–2881. doi: 10.1002/ps.5457

Parker, K. M., Barragán Borrero, V., van Leeuwen, D. M., Lever, M. A., Mateescu, B., and Sander, M. (2019). Environmental fate of RNA interference pesticides: adsorption and degradation of double-stranded RNA molecules in agricultural soils. *Environ. Sci. Technol.* 53, 3027–3036. doi: 10.1021/acs.est.8b05576

Petek, M., Coll, A., Ferenc, R., Razinger, J., and Gruden, K. (2020). Validating the potential of double-stranded RNA targeting Colorado potato beetle *mesh* gene in laboratory and field trials. *Front. Plant Sci.* 11, 1250. doi: 10.3389/fpls.2020.01250

Pittelkow, C. M., Liang, X., Linquist, B. A., van Groenigen, K. J., Lee, J., Lundy, M. E., et al. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature* 517, 365–368. doi: 10.1038/nature13809

Priyadarshana, T. S., Lee, M.-B., Ascher, J. S., Qiu, L., and Goodale, E. (2021). Crop heterogeneity is positively associated with beneficial insect diversity in subtropical farmlands. *J. Appl. Ecol.* 58, 2747–2759. doi: 10.1111/1365-2664.14005

Rank, A. P., and Koch, A. (2021). Lab-to-field transition of RNA spray applications – How far are we? *Front. Plant Sci.* 12, 2243. doi: 10.3389/fpls.2021.755203

Reich, J., Paul, S. S., and Snapp, S. S. (2021). Highly variable performance of sustainable intensification on smallholder farms: a systematic review. *Glob. Food Sec.* 30, 100553. doi: 10.1016/j.gfs.2021.100553

Ricciardi, V., Mehrabi, Z., Wittman, H., James, D., and Ramankutty, N. (2021). Higher yields and more biodiversity on smaller farms. *Nat. Sustain.* 4, 651–657. doi: 10.1038/s41893-021-00699-2

Rodriguez, C., Dimitrova Mårtensson, L.-M., Zachrison, M., and Carlsson, G. (2021). Sustainability of diversified organic cropping systems—Challenges identified by farmer interviews and multi-criteria assessments. *Front. Agron.* 3, 75. doi: 10.3389/fagro.2021.698968

Schulz, R., Bub, S., Petschick, L. L., Stehle, S., and Wolfram, J. (2021). Applied pesticide toxicity shifts toward plants and invertebrates, even in GM crops. *Science* 372, 81–84. doi: 10.1126/science.abe1148

Sgolastra, F., Arnan, X., Cabbri, R., Isani, G., Medrzycki, P., Teper, D., et al. (2018). Combined exposure to sublethal concentrations of an insecticide and a fungicide affect feeding, ovary development and longevity in a solitary bee. *Proc. R. Soc. B* 285, 20180887. doi: 10.1098/rspb.2018.0887

Simon-Delso, N., Martin, G. S., Bruneau, E., and Hautier, L. (2018). Time-to-death approach to reveal chronic and cumulative toxicity of a fungicide for honeybees not revealed with the standard ten-day test. *Sci. Rep.* 8, 7241. doi: 10.1038/s41598-018-24746-9

The Earth BioGenome Project (2018). *Earth BioGenome Project*. Available online at: https://www.earthbiogenome.org (accessed December 16, 2021).

United Nations (2022). *Sustainable Development*. Available online at: https://sdgs.un.org/ (accessed January 18, 2022).

United Nations Environment Programme and Food and Agriculture Organization of the United Nations (2020). *The UN Decade on Ecosystem Restoration 2021-2030*. Available online at: https://wedocs.unep.org/bitstream/handle/20.500.11822/30919/UNDecade.pdf?sequence=11 (accessed January 17, 2022).

Wagaba, H., Kuria, P., Wangari, P., Aleu, J., Obiero, H., Beyene, G., et al. (2021). Comparative compositional analysis of cassava brown streak disease resistant 4046 cassava and its non-transgenic parental cultivar. *GM Crops Food* 12, 158–169. doi: 10.1080/21645698.2020.1836924

Willow, J., Silva, A., Veromann, E., and Smagghe, G. (2019). Acute effect of low-dose thiacloprid exposure synergised by tebuconazole in a parasitoid wasp. *PLoS ONE* 14, e0212456. doi: 10.1371/journal.pone.0212456

Willow, J., Soonvald, L., Sulg, S., Kaasik, R., Silva, A. I., Taning, C. N. T., et al. (2021a). RNAi efficacy is enhanced by chronic dsRNA feeding in pollen beetle. *Commun. Biol.* 4, 1–8. doi: 10.1038/s42003-021-01975-9

Willow, J., Taning, C. N. T., Cook, S. M., Sulg, S., Silva, A. I., Smagghe, G., et al. (2021b). RNAi targets in agricultural pest insects: advancements, knowledge gaps, and IPM. *Front. Agron.* 3, 99. doi: 10.3389/fagro.2021.794312

Willow, J., and Veromann, E. (2021). Highly variable dietary RNAi sensitivity among Coleoptera. *Front. Plant Sci.* 12, 2914. doi: 10.3389/fpls.2021.790816

Worrall, E. A., Bravo-Cazar, A., Nilon, A. T., Fletcher, S. J., Robinson, K. E., Carr, J. P., et al. (2019). Exogenous application of RNAi-inducing double-stranded RNA inhibits aphid-mediated transmission of a plant virus. *Front. Plant Sci.* 10, 265. doi: 10.3389/fpls.2019.00265

Wytinck, N., Manchur, C. L., Li, V. H., Whyard, S., and Belmonte, M. F. (2020). dsRNA uptake in plant pests and pathogens: insights into RNAi-based insect and fungal control technology. *Plants* 9, 1780. doi: 10.3390/plants9121780

Yan, S., Qian, J., Cai, C., Ma, Z., Li, J., Yin, M., et al. (2020). Spray method application of transdermal dsRNA delivery system for efficient gene silencing and pest control on soybean aphid *Aphis glycines*. *J. Pest Sci.* 93, 449–459. doi: 10.1007/s10340-019-01157-x

Zheng, Y., Hu, Y., Yan, S., Zhou, H., Song, D., Yin, M., et al. (2019). A polymer/detergent formulation improves dsRNA penetration through the body wall and RNAi-induced mortality in the soybean aphid *Aphis glycines*. *Pest Manag. Sci.* 75, 1993–1999. doi: 10.1002/ps.5313

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher's Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers | Frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 31 May 2022
doi: 10.3389/fsufs.2022.878015

# Impact of Natural Farming Cropping System on Rural Households—Evidence From Solan District of Himachal Pradesh, India

*Chinglembi Laishram [1]*, Rohit Kumar Vashishat [1], Subhash Sharma [1], Bhavna Rajkumari [2], Neha Mishra [3], Parul Barwal [1], Manoj Kumar Vaidya [1], Ravinder Sharma [4], Rajeshwar Singh Chandel [5], Ashu Chandel [3], Rakesh Kumar Gupta [3] and Neha Sharma [6]*

*[1] Department of Social Sciences, Dr. YS Parmar University of Horticulture and Forestry, Solan, India, [2] Department of Seed Science and Technology, Dr. YS Parmar University of Horticulture and Forestry, Solan, India, [3] Department of Basic Sciences, Dr. YS Parmar University of Horticulture and Forestry, Solan, India, [4] Directorate of Research, Dr. YS Parmar University of Horticulture and Forestry, Nauni, India, [5] State Project Implementation Unit (SPIU), Shimla, India, [6] Department of Biotechnology, Amity University, Noida, India*

**Edited by:**
*Sendhil R.,*
*Pondicherry University, India*

**Reviewed by:**
*Subhash Chandra Tripathi,*
*Indian Institute of Wheat and Barley Research (ICAR), India*
*R. Jayakumara Varadan,*
*Central Island Agricultural Research Institute (ICAR), India*
*Geretharan Thangavelautham,*
*Eastern University, Sri Lanka*
*Sreenath Dixit,*
*International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India*
*Kiran Kumar T. M.,*
*National Institute for Agricultural Economics and Policy Research (NIAP), India*

***Correspondence:**
*Chinglembi Laishram*
*chinglaish@gmail.com*

**Specialty section:**
*This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems*

**Received:** *17 February 2022*
**Accepted:** *08 April 2022*
**Published:** *31 May 2022*

**Citation:**
*Laishram C, Vashishat RK, Sharma S, Rajkumari B, Mishra N, Barwal P, Vaidya MK, Sharma R, Chandel RS, Chandel A, Gupta RK and Sharma N (2022) Impact of Natural Farming Cropping System on Rural Households—Evidence From Solan District of Himachal Pradesh, India. Front. Sustain. Food Syst. 6:878015. doi: 10.3389/fsufs.2022.878015*

Natural farming, popularly known as zero budget natural farming, is an innovative farming approach. It is low input based, climate resilient, and low cost farming system because all the inputs (insect repellents, fungicides, and pesticides) are made up of natural herbs and locally available inputs, thereby reducing the use of artificial fertilizers and industrial pesticides. It is becoming increasingly popular among the smallholder farmers of Himachal Pradesh. Under the natural farming system, 3 to 12 crops are cultivated together on the same area, along with leguminous crops as intercrop in order to ensure that no piece of land is wasted and utilized properly. This article focuses mainly on the different cropping systems of natural farming and comparing the economics of natural farming (NF) with conventional farming (CF) systems. Study shows that farmers adopted five major crop combinations under natural farming system, i.e., vegetables-based cropping system (e.g., tomato + beans + cucumber and cauliflower + pea + radish), vegetables-cereals-based cropping system, and other three more cropping systems discussed in this article. The results indicated that a vegetable-based cropping system has 19.68% more net return in Kharif season and 24.64% more net return in Rabi season as compared to conventional farming vegetable-based monocropping system. NF maximizes land use and reduces the chance of crop yield loss. NF has resulted in increased returns especially in the vegetable cropping system where reduction in cost was 30.73 per cent (kharif) and 11.88 per cent (rabi) across all crop combinations in comparison to CF. It is found in study that NF was cost savings from not using chemical fertilizers and pesticides, as well as higher benefit from intercrops.

**Keywords: natural farming, sustainability, crop combinations, intercropping, Himachal Pradesh**

## INTRODUCTION

For around 58% of India's population, agriculture is their major source of income. Agriculture, forestry, and fishery had a gross value added of Rs 19.48 lac crore (US$ 276.37 billion) in fiscal year 2020. In fiscal year (FY) 2020, agricultural and allied industries accounted for 17.8% of India's gross value added (GVA) at current prices. Consumer expenditure in India would increase by as much as 6.6% in 2021. India's share in world agricultural exports increased to 2.1% in 2019 from 1.71% in 2010 (Ministry of Commerce, 2021).

The country achieved its remarkable agricultural growth in the 1960s, after the emergence of the Green Revolution. India marked a new era in Indian agricultural history. The Green Revolution technology aimed to increase agricultural production mainly by substituting typically hardy plant varieties with high-response varieties and hybrids, the use of fertilizers and plant protection chemicals, irrigating more cultivated land by investing heavily on large irrigation systems, and consolidation of agricultural holdings (Sebby, 2010). India has gained its outstanding position in food production, but it is also facing a poor ranking in the hunger index (Menon et al., 2008). The Green Revolution left its harmful footprints on Indian agriculture. The monocropping system, increased and frequent use of fertilizers and pesticides caused considerable damage to the soil's biological operation, crop diversity, increased cost of cultivation, deterioration of groundwater, loss of flora-fauna, increased human diseases, malnutrition, and decreased soil fertility, which have almost left it barren in large areas. As a consequence, farmers with small farms invest in these costly inputs, which are exposed to high monetary risks and push them in the debt cycle (Eliazer et al., 2019). With pesticides' obvious environmental and ecological effects, it is no surprise that government laws have been strengthened (Carrington, 2019). Furthermore, the possible health implications of pesticide residue have terrified many of us into choosing pesticide-free items. Even though rules exist to assure legal maximum residual levels that have been considered scientifically acceptable for food, the campaign to eliminate pesticides has gained traction. Restoring soil health by reverting to non-chemical agriculture has assumed great importance in achieving sustainability in production.

In India, a chemical-free and climate-resilient method of farming given by a scientist Subhash Palekar, during 2006 in Maharashtra to end the problems arising after the Green Revolution by introducing natural farming. His methods popularized when farmers started adopting his methods. After that, many researchers and scientists claimed that natural farming is a good alternative to chemical farming that directly or indirectly impacts sustainable development positively (Tripathi and Tauseef, 2018). The aim of natural farming is to reduce the cost of production to almost zero and to come back to the "pre-Green Revolution" style of agriculture (Khadse et al., 2017). This would seem to lead growers out of loans by putting a stop to agricultural chemicals practices. The central government has implemented a policy to encourage farming methods throughout India. The state governments of Andhra Pradesh, Chhattisgarh, Himachal Pradesh, Uttarakhand, Kerala, and Karnataka asked Subhash Palekar to educate their farmers for natural farming (Khadse and Rosset, 2019a,b).

In order to promote natural farming in Himachal Pradesh, a scheme "Prakritik Kheti Khushhal Kisan" was initiated with a budget allocation of Rs 35 crore (2019–2020). Under this scheme, peasants will be supported with training, the required machinery, to achieve the objective of sustainable farming doubling farmers' incomes, improved soil fertility, and low input costs (Vashishat et al., 2021). Though the search for a better alternative shall always remain, right now natural farming is a credible alternative itself (Mishra, 2018).

Natural farming is a special form of agriculture that does not requires any financial expenditure to purchase the essential inputs such as seeds, fertilizers, and plant protection chemicals from the market. Natural farming, though in its preliminary stages, is showing increased positive results and is being adopted by farmers in good faith. It is even cited by farmers that labor and production costs have drastically reduced 14–45% (Chandel et al., 2021).

The cropping system of natural farming focuses mainly on traditional Indian practices based on agroecology; natural farming absolutely requires no monetary investment for purchase of key inputs at all (Palekar, 2005). Due to its simplicity, adaptiveness, and huge reduction in cost of cultivation to know the impact of the cropping system of natural farming on the small and marginal farmers, this study was conducted.

The objectives of this study will be:

i) To study the socioeconomic status of the farmers.
ii) To study the comparative economics of natural farming vis-à-vis conventional farming.
iii) To identify the constraints of natural farming.

## METHODOLOGY

### Selection of the Study Area and Respondents

Solan district of Himachal Pradesh was purposely selected for this study. The district comprises five development blocks, i.e., Dharampur, Kandaghat, Nalagarh, Solan, and Kunihar. Out of these, three blocks were selected randomly and a list of farmers practicing both the Subhash Palekar Natural Farming (SPNF) and conventional farming were procured from the Project Director ATMA, Solan. From the list, 20 farmers each from the three selected blocks were selected randomly. Thus, total samples of 60 farmers were selected for this study. The primary data were collected from the farmers practicing both the natural farming and conventional farming systems by survey method using a well-structured and pre-tested schedule (questionnaire).

### Distribution of Sampled Farmers Practicing Natural Farming According to Their Size of Landholding

For the analysis of data, the total respondents were divided according to the size of their landholdings into three classes, viz., marginal (<1 ha), small (1–2 ha), and medium (2–4 ha). The distribution of the sampled farmers is given in **Table 1**.

**TABLE 1 |** Distribution of sampled households according to their landholdings.

| Sr. no. | Category of farmer | No. of farmers | Average size of land holding (ha) |
|---|---|---|---|
| 1. | Marginal (< 1 ha) | 33 (55) | 0.51 |
| 2. | Small (1–2 ha) | 17 (28.33) | 1.09 |
| 3. | Medium (2–4 ha) | 10 (16.67) | 2.02 |
| 4. | Total | 60 (100) | 1.68 |

*Figures in parentheses are percentage to the total.*

# ANALYTICAL FRAMEWORK

To fulfill the above specified objectives of this study, based on the nature and extent of availability of data, the following analytical tools and techniques have been employed for the analysis of the data.

## Tabular Analysis

Simple tabular analysis was used to examine socioeconomic status, resource structure, income and expenditure pattern, and farmers' opinions about the production and marketing problems under natural farming. Simple statistical tools such as averages and percentages were used to compare, contrast, and interpret the results. The sex ratio, literacy rate, and index were calculated using the following formulae:

$$\text{Literacy rate} = \frac{\text{Total no. of literate person}}{\text{Total population}} \times 100$$

$$\text{Literacy Index} = \frac{\sum W_iX_i}{\sum X_i}$$

Where,

$W_i$ = Weights (0, 1, 2, 3, 4, and 5) for illiterate, primary, middle, metric, secondary, and graduate and above, respectively.

$X_i$ = Number of persons in respective category.

$$\text{Dependency ratio w.r.t. total workers} = \frac{\text{No. of dependents in a family}}{\text{Total workers}}$$

$$\text{Dependency ratio w.r.t. average size of family} = \frac{\text{No. of dependents in a family}}{\text{Family Size}}$$

$$\text{Cropping intensity} = \frac{\text{Gross cropped area}}{\text{Net sown area}} \times 100$$

## Costs and Returns Analysis

### Commission for Agricultural Costs and Prices Cost Concepts

**Cost $A_1$ includes:**

i) Cost of planting material cost
ii) Cost of manures, fertilizers, and plant protections
iii) Cost of hired human labor
iv) Cost of owned and hired machinery
v) Irrigation charges
vi) Depreciation on implements, farm buildings, and irrigation structures
vii) Land revenue
viii) Interest on owned working capital
ix) Other miscellaneous charges.

- **Cost $A_2$:** Cost $A_1$ + rent paid for leased-in land
- **Cost $B_1$:** Cost $A_1$ + interest on the fixed capital assets excluding land
- **Cost $B_2$:** Cost $B_1$ + rental value of owned land
- **Cost $C_1$:** Cost $B_1$ + imputed value of family labor
- **Cost $C_2$:** Cost $B_2$ + imputed value of family labor
- **Cost $C_3$:** Cost $C_2$ + 10% of cost $C_2$ on account of managerial function performed by the farmer.

### Crop Equivalent Yield

In natural farming system, many types of crops were cultivated in a multiple or mixed cropping. So, it was very difficult to compare the economics of multiple crops with a single crop. Francis (1986) described crop equivalent yield (CEY) to the sum of equivalent principal and intercrop yields. The differing yield intercrops were transformed into the equivalent yield of any crop depending on the commodity price. So, a comparison was made based on economic returns and crop equivalent yield (CEY) of multiple cropping sequences was calculated by converting the yield of different intercrops/crops into equivalent yield of any one crop based on price of the produce. Mathematically, the CEY is represented as:

$$\text{CEY} = C_Y + C_{Y1}\frac{P_1}{P_0} + C_{Y2}\frac{P_2}{P_0} \ldots .$$

Where,

$C_Y$ = Yields of the main crop

$P_0$ = Price of the main crop

($C_{y1}$, $C_{y2}$, $C_{y3.....}C_{yn}$) = Yields of intercrop, which are to be converted to equivalent of main crop yield

($P_1$, $P_2$, $P_3\ldots$ $P_n$) = Price of the respective intercrops.

### Relative Economic Efficiency

Farrell (1957) distinguished three types of efficiency, namely, technical efficiency, price or allocative efficiency, and economic efficiency (which is a combination of the first two). Economic efficiency is distinct from the other two efficiencies, even though it is the product of technical and allocative efficiencies. Relative economic efficiency, which is a comparative measure of economic gains, can be calculated by:

$$\text{REE} = \frac{\text{Net Returns in Natural Farming} - \text{Net Returns in Conventional Farming}}{\text{Net Returns in Conventional Farming}} \times 100$$

### Statistical Analysis

The comparative economics was statistically analyzed as per the procedure given by Gomez and Gomez (1984). The ANOVA was carried out based on the model in **Table 2**.

**TABLE 2 |** ANOVA (two-rowed without replication) layout.

| Source of variation | SS | *df* | MS | *F* | *P*-value (at 0.05) | *F* crit |
|---|---|---|---|---|---|---|
| **ANOVA** | | | | | | |
| Rows | SSr | r-1 | MSr = SSr/(r-1) | MSr/MSe | — | — |
| Columns | SSc | c-1 | MSc = SSc/(c-1) | MSc/MSe | — | — |
| Error | SSe | (r-1)(c-1) | MSe = SSe/(r-1)(c-1) | | | |
| Total | SSt | rc-1 | | | | |

*r, No. of rows; c, No. of columns.*

## Production and Marketing Problems

To study the various problems associated with the production and marketing of natural farming, it was assumed that the extent of a particular problem varies from place to place and farmer to farmer. The multiple responses of producers reporting various problems were taken into consideration for analysis.

### Garrett's Ranking Technique

The Garrett's ranking technique (Garrett and Woodworth, 1969) was used for examination of constraints. It is important to note here that these constraints were focused on the response of all the sample farmers. The respondents were asked to rank the problems in turmeric and cotton production, processing, and marketing. In the Garrett's ranking technique, these ranks were converted into percent position by using the formula:

$$\text{Percent position} = \frac{100(R_{ij} - 0.5)}{N_j}$$

Where,

$R_{ij}$ = Ranking given to the ith attribute by the jth individual
$N_j$ = Number of attributes ranked by the jth individual.

By referring to the Garrett's table, the percentage positions estimated were converted into scores. Thus, for each factor, the scores of the various respondents were added and the mean values were estimated. The mean values, thus, obtained for each of the attributes were arranged in descending order. The attributes with the highest mean value were considered as the most important one and the others followed in that order.

### Chi-Squared Test

To test whether there was any significant difference among marginal, small and medium farms of Solan for the problems faced by them, chi-square test (Pearson, 1900) in (m × n) contingency table was applied where m and n are the number of marketing problems faced by the farmers of natural farming in Solan district. The detail of approximate chi-squared test is given as under:

$$\sum_{j=1}^{L}\sum_{i=1}^{K}\frac{(O_i - E_i)^2}{E_i} \sim \chi 2\ (L-1)(K\ (L1)\ \text{d.f.}$$

Where,

O = Observed values
E = Expected values
K = Number of problems
L = Number of the farm size groups.

# RESULTS AND DISCUSSION: SOCIO-ECONOMIC CHARACTERISTICS OF SAMPLED HOUSEHOLDS

## Size and Structure of the Sampled Households in the Study Area

The size and structure of the family play an important part in influencing crop production. The size and structure of the sampled households in the study area are given in **Table 3**. At an overall level, the average family size was 5.28 out of which 51.64% were males, 39.66% were females, and 8.70% were children. The average family size ranged from 5.21 to 5.35 and was observed highest in the small farmers (5.35) followed by medium farmers (5.30) and marginal farmers (5.21). The results indicated that the dominant family structure in the area under study was the nuclear family (66.67%). It was highest in small farms (47.06%) followed by marginal (30.30%) and medium farm categories (20%).

## Literacy Status of the Sampled Households

Literacy is an indicator of an individual's educational status and level of education enabling him/her to engage and participate in enhancing and improving the social and economic well-being of the surroundings. Good literacy skills open up doors for education and jobs, so people can avoid poverty and underemployment. The rate of literacy is a reflection of good human capital. Higher literacy leads to a higher level of awareness, interaction with new inventions and technologies, etc. The literacy status of the sampled households is given in **Table 4**. It is revealed from **Table 4** that the overall literacy rate was 89.70% in males and 77.52% in females and the highest literacy rate was observed in the small farm category with 91.30% in males and 78.05% in females. **Table 4** shows that 23.55% males and 7.35% females had education level upto graduation and above. The literacy index varied from 1.58 to 2.30 in males among different farm categories, while the literacy index varied from 1.73 to 2.26 in females among different farm categories, which clearly show the poor quality of education. As the level of education increases, nowadays people understand the importance of better healthcare and due to that many farmers have started to focus

**TABLE 3 |** Demographic profile of sampled households in the study area (No.).

| Particulars | Farm category | | | |
|---|---|---|---|---|
| **Family structure** | **Marginal** | **Small** | **Medium** | **Overall** |
| 1. Joint family | 10.00 (30.30) | 8.00 (47.06) | 2.00 (20.00) | 20.00 (33.33) |
| 2. Nuclear family | 23.00 (69.70) | 9.00 (52.94) | 8.00 (80.00) | 40.00 (66.67) |
| 3. Total | 33.00 (100.00) | 17.00 (100.00) | 10.00 (100.00) | 60.00 (100.00) |
| **Family size** | | | | |
| 1) Male | 2.66 (51.16) | 2.70 (50.55) | 2.90 (54.72) | 2.72 (51.64) |
| 2) Female | 2.06 (39.54) | 2.23 (41.76) | 1.90 (35.85) | 2.09 (39.66) |
| 3) Children | 0.48 (9.30) | 0.41 (7.69) | 0.50 (9.43) | 0.45 (8.70) |
| Average family size | 5.21 (100.00) | 5.35 (100.00) | 5.30 (100.00) | 5.28 (100.00) |

*Figures in parentheses are percentage to average family size.*

**TABLE 4 |** Farm category-wise literacy status of sampled households (%).

| Particulars | Farm categories | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Marginal | | Small | | Medium | | Overall | |
| | Male | Female | Male | Female | Male | Female | Male | Female |
| Illiterate | 11.11 | 21.62 | 8.70 | 20.93 | 9.68 | 21.05 | 10.18 | 21.32 |
| Primary | 5.56 | 10.8 | 2.17 | 20.93 | 32.26 | 0 | 9.58 | 12.50 |
| Middle | 21.11 | 17.57 | 21.74 | 11.63 | 12.90 | 21.05 | 19.76 | 16.18 |
| High school | 15.56 | 25.68 | 26.09 | 18.60 | 12.90 | 15.79 | 17.96 | 22.06 |
| Sr.Sec | 18.89 | 12.16 | 21.74 | 13.95 | 9.68 | 31.58 | 17.96 | 15.44 |
| Graduation | 25.55 | 5.41 | 19.57 | 9.30 | 22.58 | 10.53 | 23.35 | 7.35 |
| Non-school going (below 5 yrs) | 2.22 | 6.75 | 0 | 4.65 | 0 | 0 | 1.19 | 5.14 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Literacy rate | 88.64 | 76.81 | 91.30 | 78.05 | 90.32 | 78.95 | 89.70 | 77.52 |
| Literacy index | 2.00 | 1.90 | 2.30 | 1.73 | 1.58 | 2.26 | 2.00 | 1.90 |

more on natural farming and have no adverse impact on human health.

## Occupational Distribution of the Sampled Households

The occupational patterns play a very significant role in ascertaining the economic status of the family. In this way, we know about the households engaged in various activities such as agriculture, business, and government or private services. In developing countries, the majority of the population are still engaged in agricultural activities and other primary activities. When the area is more developed, the employment patterns will be more diversified and household incomes will also increase. Development and progress of employment are very much linked to economic development. The occupational structure, allocation of workers, and number of dependents are shown in **Table 5**.

The workforce reflects the distribution of members of the household making a contribution to the household economy. A family with more working people will be much more precise in terms of their livelihood strategies. **Table 5** concludes that 81.33% of the households are engaged in agriculture, which means that agriculture being the main occupation in the study area. With the growing importance of natural farming, farmers have become more aware of the importance of health benefits and, hence, the percentage of farmers engaged in this sector is coming out highest as compared to business and services. On an average, 2.90 per worker were engaged in business and public/private sector (15.77%), respectively.

The largest proportion of productive agricultural workers was observed in the medium farm category with 83.33% followed by the marginal (81.75%) and small farm categories (70.10%). So, as far as the average number of dependents is concerned, the highest percentage was observed in the marginal farm (26.74%) followed by the small farm (26.37%) and lowest in the medium farm category (24.53%). At the overall level, productive workers were 3.88 and varied from 3.82 to 4.00 in the marginal to medium farm categories. The overall dependency ratio with respect to workers was (1:0.35) and among the different categories, the highest was observed in marginal category (1:0.37), followed by small (1:0.36) and medium farm categories (1:0.33). Dependency result illustrates that on average, one worker has to support less than one member of the family in the sampled household.

**TABLE 5 |** Farm category-wise occupational distribution of the sampled households (No.).

| Sr. no. | Particulars | Farm categories | | | |
|---|---|---|---|---|---|
| | | Marginal | Small | Medium | Overall |
| I | Agriculture | 3.12 (81.75) | 3.12 (79.10) | 4.00 (83.33) | 3.27 (81.33) |
| II | Business | 0.09 (2.38) | 0.24 (5.97) | 0.00 (0.00) | 0.12 (2.90) |
| III | Services | 0.61 (15.87) | 0.59 (14.93) | 0.80 (16.67) | 0.63 (15.77) |
| | Average no. of workers | 3.82 (73.26) | 3.94 (73.63) | 4 (75.47) | 3.88 (62.44) |
| | Average no. of dependents | 1.39 (26.74) | 1.41 (26.37) | 1.30 (24.53) | 1.40 (37.56) |
| | Average family size | 5.21 (100) | 5.35 (100) | 5.30 (100) | 5.28 (100) |
| | Dependency ratio w.r.t workers | 0.37 | 0.36 | 0.33 | 0.35 |
| | Dependency ratio w.r.t family size | 0.27 | 0.26 | 0.25 | 0.26 |

*Figures in parentheses are percentage to average number of workers.*

**TABLE 6 |** Gender-wise distribution of the farm workers in the sampled households (No.).

| Particulars | Marginal | Small | Medium | Overall |
|---|---|---|---|---|
| Male | 1.67 (52.94) | 1.59 (49.09) | 2.50 (62.50) | 1.79 (53.81) |
| Female | 1.45 (47.06) | 1.53 (50.91) | 1.50 (37.50) | 1.48 (46.19) |
| Average no. of farm workers | 3.12 (100) | 3.12 (100) | 4.00 (100) | 3.27 (100) |

*Figures in parentheses are percentages to the total.*

**Table 6** reveals that the majority of the workforce were the males (53.81 %), while the female workers constituted 46.19%. The percentage of the male workers was the highest in medium farm category (62.50%) followed by marginal (52.94%) and small farm categories (49.09%). The proportion of female workers was considered to be the highest (50.91%) in the small farm category followed closely by the marginal (47.06%) and medium-farm categories (37.50%).

## Season-Wise Major Crop Combinations Under Natural Farming System

Under natural farming system, three to four crops are cultivated or grown together on the same area, along with leguminous crops as intercrop in order to ensure that no piece of land is wasted and utilized properly. These combinations during the growing season were established to encourage interaction between them and are based on the idea that complementarities exist between the plants. Intercropping with leguminous crops is considered as one of the most important components of natural farming as it increases crop productivity and soil fertility through the atmospheric nitrogen fixation. These complementarities between crops increase soil and its nutrients. It also involves diversification and improves profits by growing and selling various types of cereals, vegetables, legumes, fruit, and even medicinal plants. The multiple cropping systems substantially enhance income. This system maximizes land use and reduces the chance of crop yield loss. This study found that farmers grow different crops under different crop combinations in the study area. The major crop combinations adopted by the selected farmers were categorized as: (i) vegetables, (ii) vegetables-cereals, (iii) vegetables-pulses, (iv) cereals-pulses, and (v) vegetables-oilseeds crops. From **Table 7**, it was observed that in Kharif season, the major vegetable being grown in the study area was tomato and the other crops included were capsicum, cucumber, bottle gourd, chili, okra, brinjal, etc. The main intercrops (leguminous) in the study area include French bean and soybean. The major cereals and pulses include maize, beans, soybean, etc. While in Rabi season, cauliflower is the major vegetable followed by wheat, pea, and chickpea as the major cereals and pulses grown in the study area. The other crop includes radish, fenugreek, coriander, spinach, potato, onion, garlic, etc. Mustard was being grouped under as major oilseeds crops. The main leguminous crops (intercrops) in Rabi season were pea, chickpea, and kidney beans.

Now, in conventional farming, as opposed to natural farming, solo cropping is practiced. From **Table 8**, it was observed that the main crops grown by the farmers were tomato and maize in the Kharif season and in Rabi season, the main crops grown were cauliflower, wheat, chickpea, and mustard.

So, in order to compare within these two systems, one main crop is kept common between the two systems. For example, from **Table 1**, in the Kharif season, in natural farming, in vegetables crop combination, it was observed that tomato is the main crop and it was being planted along with several crops. Similarly, in **Table 8**, under conventional farming, it was seen under the vegetables section (Kharif season) that the main crop is tomato. So, in order to compare these two systems, a comparison was made based on economic returns and, henceforth, crop equivalent yield (CEY) of multiple cropping sequences was calculated by converting the differing yields of intercrops into the equivalent yield of the main crop, i.e., tomato (in case of

**TABLE 7 |** Season-wise major crop combinations under natural farming (NF) system.

| Particulars | Kharif | Rabi |
|---|---|---|
| Vegetables | Tomato + Beans + Cucumber | Cauliflower + Pea + Radish |
| | Tomato + Beans | Cauliflower + Pea + Fenugreek |
| | Tomato + Beans + Capsicum | Cauliflower + Pea + Coriander |
| | Tomato + Beans + Chili | Cauliflower + Pea + Spinach |
| | Tomato + Beans + Bottle Gourd | Cauliflower + Pea + Potato |
| | Tomato + Bean + Okra | Cauliflower + Pea + Onion |
| | Tomato + Beans + Brinjal | Onion + Pea + Fenugreek |
| | Capsicum + Beans | Cauliflower + Pea |
| | | Cabbage + Pea + Fenugreek |
| Vegetables-Cereals | Tomato + Maize + Beans | Potato + Wheat + Pea |
| | Capsicum + Maize + Beans | Cauliflower + Wheat + Pea |
| | Bottle Gourd + Maize + Beans | Colocasia + Wheat + Pea |
| | Tomato + Maize + Beans | |
| Vegetables-Pulses | Tomato + Soyabean | Cauliflower-Chickpea |
| | Tomato + Soyabean + Cucumber | Cauliflower + Kidney Beans + Potato |
| | Tomato + Soyabean + Chili | Cauliflower + Chickpea + Coriander |
| | Okra + Beans | Cauliflower + Chickpea + Fenugreek |
| Cereals-Pulses | Maize + Soyabean | Wheat + Chickpea |
| | | Wheat + Chickpea + Mustard |
| | | Wheat + Chickpea + Pea |
| Vegetables-Oil seeds | —— | Cauliflower + Mustard + Fenugreek |
| | —— | Cauliflower + Mustard + Cabbage |
| | —— | Cauliflower + Mustard + Coriander |
| | —— | Cauliflower + Mustard + Radish |
| | —— | Cauliflower + Mustard |

**TABLE 8 |** Season-wise major crop combinations under conventional farming (CF) system.

| Particulars | Kharif | Rabi |
|---|---|---|
| Vegetables | Tomato | Cauliflower |
| Vegetables-Cereals | Maize | Wheat |
| Vegetables-Pulses | Tomato | Chickpea |
| Cereals-Pulses | Maize | Wheat |
| Vegetables-Oil seeds | —— | Mustard |

vegetables crop combination for both the systems) depending on price of the produce. Similarly, CEY of other crop combinations was also calculated by using this same method mentioned above.

## Comparative Analysis of Natural Farming System and Conventional Farming System

### Yield

Under natural farming system, two or three crops are cultivated on the same farmland. Because different crop types were grown in a multiple or mixed crop system, it was hard to equate NFs economic produce with CF. So, to compare the yield, the crop equivalent yield (CEY) concept was used for a mixed cropping system. In the statistical analysis shown in **Tables 9**, **10**, we can observe that, along the rows, all the crop combinations have significantly higher yields under NF as compared to CF in both the seasons. Now, from **Table 11**, it was observed that, for all the crop combinations, the yield in the NF system was found to be higher than the CF system and it varied from 49.20 to 208.45 q/ha. The maximum yield was observed in vegetables 208.45 q/ha for the Kharif season. In the case of the Rabi season, it ranged from 48.33 to 58.12 q/ha. Same results were found like Kharif season, i.e., yield in all the crop combinations under NF was more than of CF. The maximum yield was observed in vegetables crop combination (58.12 q/ha). From **Table 11**, it was observed that CEY of the NF system was found to be greater than that of those of the CF system. All the NF crop combinations show an average increase in yield over the CF system. In the Kharif season, the increase in the yield under NF system over CF system varied from 3.08 to 5.10%, while in Rabi season, it ranged from 2.83 to 7.98% in all the crop combinations. In Kharif season, the maximum increase in yield under NF was observed in vegetables and cereals-pulses in Rabi season. The above results were supported by Tripathi and Tauseef (2018), which stated that the average of zero budget natural farming (ZBNF) groundnut farmers was 23% higher than their counterparts outside the ZBNF. On average ZBNF, paddy farmers had a 6% higher yield. These increments are the result of sustainable farming practices, which also improve farmers' capacity to adapt to climate change. Also, another study observed an increase in CEY under cereals-pulses combination (17.22%). This higher increase can be attributed to the comparative remunerative prices of pulses and symbiotic effect of pulses on cereal crop yield (Chandel et al., 2021).

### Cost of Cultivation

One of the key cost components for the production of cash crops such as fruits and vegetables under the CF system in the state is chemical inputs. This continuous farming activity has contributed to higher costs and eventually reduced incomes for farmers. A substantial decrease in the cost of growing these crops has occurred with the use of NF technology. **Tables 12**, **13** indicate the statistical analysis of the cost of cultivation where we can observe that, along the rows, all the crop combinations have significantly lower costs under NF as compared to CF in both the seasons. **Table 14** presents a comparison of cost of cultivation between NF and CF systems. It has been observed that the total cost of all the crop combinations in NF systems during the cultivation process was substantially reduced. In the

**TABLE 9 |** Statistical analysis of Kharif season from **Table 11**.

| Source of variation | SS | *df* | MS | *F* | *P*-value | *F* crit |
|---|---|---|---|---|---|---|
| **ANOVA** | | | | | | |
| Rows | 25863.47 | 3 | 8621.156 | 1487.18 | 2.96E-05 | 9.276628 |
| Columns | 58.42805 | 1 | 58.42805 | 10.07904 | 0.050297 | 10.12796 |
| Error | 17.39095 | 3 | 5.796983 | | | |
| Total | 25939.29 | 7 | | | | |

**TABLE 10 |** Statistical analysis of Rabi season from **Table 11**.

| Source of variation | SS | *df* | MS | *F* | *P*-value | *F* crit |
|---|---|---|---|---|---|---|
| **ANOVA** | | | | | | |
| Rows | 154.32116 | 4 | 38.58029 | 66.61422 | 0.00065 | 6.388233 |
| Columns | 14.78656 | 1 | 14.78656 | 25.53104 | 0.007217 | 7.708647 |
| Error | 2.31664 | 4 | 0.57916 | | | |
| Total | 171.42436 | 9 | | | | |

**TABLE 11 |** Crop equivalent yield (CEY) of various crop combinations under NF and conventional farming (CF) systems.

| Crops combination | CEY (q/ha) | | | | | |
|---|---|---|---|---|---|---|
| | Kharif | | | Rabi | | |
| | NF | CF | % increase in NF over CF | NF | CF | % increase in NF over CF |
| Vegetables | 208.45 | 198.34 | 5.10 | 60.75 | 58.12 | 4.53 |
| Vegetables+Cereals | 160.5 | 155.59 | 3.16 | 53.19 | 51.3 | 3.68 |
| Vegetables+Pulses | 155.13 | 150.5 | 3.08 | 59.79 | 57.7 | 3.62 |
| Cereals+Pulses | 49.2 | 47.23 | 4.17 | 56.54 | 52.36 | 7.98 |
| Vegetables+Oilseeds | - | - | - | 49.7 | 48.33 | 2.83 |

**TABLE 12 |** Statistical analysis of Kharif season from **Table 14**.

| Source of variation | SS | *df* | MS | *F* | *P*-value | *F* crit |
|---|---|---|---|---|---|---|
| **ANOVA** | | | | | | |
| Rows | 13527216 | 3 | 4509072 | 62.84556 | 0.003312 | 9.276628 |
| Columns | 1.29E+08 | 1 | 1.29E+08 | 1793.277 | 2.9E-05 | 10.12796 |
| Error | 215245.4 | 3 | 71748.46 | | | |
| Total | 1.42E+08 | 7 | | | | |

**TABLE 13 |** Statistical analysis of Rabi season from **Table 14**.

| Source of variation | SS | *df* | *MS* | *F* | *P*-value | *F* crit |
|---|---|---|---|---|---|---|
| **ANOVA** | | | | | | |
| Rows | 4.3E+08 | 4 | 1.08E+08 | 159.4464 | 0.000116 | 6.388233 |
| Columns | 78596123 | 1 | 78596123 | 116.5028 | 0.000418 | 7.708647 |
| Error | 2698515 | 4 | 674628.8 | | | |
| Total | 5.12E+08 | 9 | | | | |

Kharif season, the percentage reduction in NF cultivation costs over the CF system ranged from 12.56 to 30.73%, while in the Rabi season it ranged from 6.86 to 12.34%. In Kharif season, maximum reduction in cost was observed in vegetables crop combination, whereas in case of Rabi season, the maximum reduction was observed in cereal-pulses crop combination. This

**TABLE 14 |** Cost of cultivation of various crop combinations under NF and CF systems.

| Crops combination | Cost of cultivation (Rs/ha) | | | | | |
|---|---|---|---|---|---|---|
| | Kharif | | | Rabi | | |
| | Total cost | | % change in NF over CF | Total cost | | % change in NF over CF |
| | NF | CF | | NF | CF | |
| Vegetables | 55,056 | 79,485 | −30.73 | 55,511 | 62,992 | −11.88 |
| Vegetables+Cereals | 55,302 | 70,117 | −21.13 | 59,288 | 63,652 | −6.86 |
| Vegetables+Pulses | 54,478 | 72,304 | −24.65 | 57,354 | 62,754 | −8.60 |
| Cereals+Pulses | 52,359 | 59,880 | −12.56 | 40,605 | 46,322 | −12.34 |
| Vegetables+Oilseeds | - | - | - | 52,374 | 57,447 | −8.83 |

**TABLE 15 |** Statistical analysis of Kharif season from **Table 17**.

| Source of variation | SS | *df* | MS | *F* | *P*-value | *F* crit |
|---|---|---|---|---|---|---|
| **ANOVA** | | | | | | |
| Rows | 8.04E +1 0 | 3 | 2.68E + 10 | 707.1091 | 9.01E-05 | 9.276628 |
| Columns | 2.39E + 08 | 1 | 2.39E + 08 | 6.321019 | 0.08662 | 10.12796 |
| Error | 1.14E + 08 | 3 | 37887489 | | | |
| Total | 8.07E + 10 | 7 | | | | |

**TABLE 16 |** Statistical analysis of Rabi season from **Table 17**.

| Source of variation | SS | *df* | MS | *F* | *P*-value | *F* crit |
|---|---|---|---|---|---|---|
| **ANOVA (Rabi)** | | | | | | |
| Rows | 1.6E+09 | 4 | 4.01E+08 | 584.8605 | 8.73E-06 | 6.388233 |
| Columns | 7250523 | 1 | 7250523 | 10.57951 | 0.031298 | 7.708647 |
| Error | 2741345 | 4 | 685336.3 | | | |
| Total | 1.61E+09 | 9 | | | | |

indicates that the NF method lowers the costs of farmers as it uses non-synthetic inputs locally in contrast to CF capital intensive inputs. Similar findings have been published, which revealed that, after converting into ZBNF, farmers had a decreased cost of cultivation for all the crops and, most significantly, farmers were able to increase their income from natural agricultural practices by increasing the number of crops (Mishra, 2018). In another study, it was observed that the total cost of cultivation was reduced across all the crop combinations. The total expenditure in fruit-based cropping sequences showed a marked decline from Rs. 2,40,638 to Rs. 1,31,023 per ha., which indicate that the SPNF system reduces farmers' direct costs, boosting yields, and promotes the use of locally sourced non-synthetic inputs, compared to capital intensive CF (Chandel et al., 2021).

Conventional farming currently faces numerous challenges such as decreasing factor productivity, inappropriate and imbalanced use of nutrients, poor water and nutrient quality, depletion of natural resources, and increased input costs. Different crop combinations have clearly demonstrated that chemical-based farming technologies are highly capital intensive.

## Net Returns

The profits and losses of a farm are reflected through its net income. It constitutes gross returns from the business after deduction of total cost incurred. In NF, input costs are highly diminished due to the abstinence from pesticides, insecticides, and adoption of natural inputs such as *jivamrit*, *bijamrit*, *ghanjivamrit*, and *neemastra*. NF inputs and other natural preparations have a major impact due to reduced expenditure on chemical fertilizers and pesticides. The statistical analysis for net returns under NF and CF is shown in **Tables 15**, **16**. Here, it is very apparent that, along the rows, all the crop combinations have significantly higher net returns under NF as compared to CF in both the seasons. Furthermore, **Table 17** reveals that net returns in NF were higher than CF across all the crop combinations. The relative economic efficiency (REE), the comparative measure of economic gain in NF over the CF in all the crop combinations in the Kharif season, was 13.20 to 23.05% higher, while in the Rabi season, it was 24.16 to 31.30% higher in all the crop combinations. Maximum relative economic efficiency was observed in the cereals-pulses crop combination in the Kharif season and in Rabi season, the maximum relative economic efficiency was

**TABLE 17 |** Crop combination-wise net returns under NF and CF systems.

| Crops combination | Net returns (Rs/ha) | | | | | |
|---|---|---|---|---|---|---|
| | Kharif) | | | Rabi | | |
| | Net returns | | Relative economic efficiency (%) | Net returns | | Relative Economic Efficiency (%) |
| | NF | CF | | NF | CF | |
| Vegetables | 272,875 | 228,009 | 19.68 | 54,895 | 44,038 | 24.65 |
| Vegetables + Cereals | 245,648 | 215,284 | 14.10 | 34,007 | 27,390 | 24.16 |
| Vegetables + Pulses | 210,940 | 186,346 | 13.20 | 29,393 | 22,386 | 31.30 |
| Cereals + Pulses | 12,178 | 9,897 | 23.05 | 30,843 | 24,252 | 27.18 |
| Vegetables + Oilseeds | — | — | — | 27,886 | 22,409 | 24.44 |

**TABLE 18 |** Farm category-wise problem faced by natural farming producer in study area (Multiple response, %).

| Sr. no. | Problems | Marginal | Small | Medium | Overall | Chi square |
|---|---|---|---|---|---|---|
| | No. of farmers | 33 | 17 | 10 | 60 | 60 |
| 1. | Skilled labor | | | | | |
| a) | Shortage of skilled labor | 34.15 | 63.64 | 50.00 | 45.14 | 8.84 |
| b) | Higher wages rates | 17.07 | 27.27 | 37.50 | 23.37 | 7.65 |
| c) | Non-availability at peak operation time | 4.88 | 18.18 | 25.00 | 12.00 | 13.07 |
| 2. | Natural fertilizer | | | | | |
| a) | High preparing cost | 31.71 | 27.27 | 50.00 | 33.50 | 7.99 |
| b) | Inadequate training facilities | 24.39 | 18.18 | 37.00 | 24.82 | 7.29 |
| c) | Lack of extension facilities | 19.51 | 36.36 | 25.00 | 25.20 | 5.48 |
| d) | Inputs not available in time | 17.07 | 18.18 | 12.50 | 16.63 | 1.14 |
| 3. | Lack of knowledge of package of practices | 19.51 | 45.45 | 37.50 | 29.86 | 10.34 |
| 4. | Irrigation facility not available | 7.32 | 18.18 | 12.50 | 11.26 | 4.66 |
| 5. | Non-availability of buyers | 12.20 | 27.27 | 25.00 | 18.60 | 6.15 |
| 6. | Higher commission | 7.32 | 18.18 | 25.00 | 13.34 | 9.45 |
| 7. | Wholesalers not taking consent while selling | 4.88 | 9.09 | 0.00 | 5.26 | 8.89 |
| 8. | Delay in payments | 12.12 | 17.65 | 20.00 | 15.00 | 1.97 |
| 9. | Non-availability of specialized market | 65.85 | 63.64 | 62.50 | 86.37 | 14.91 |
| 10. | Lack of transport facilities | 12.20 | 27.27 | 12.50 | 16.52 | 8.58 |
| 11. | Fair price for produce in market | 70.73 | 118.18 | 87.50 | 86.97 | 12.57 |
| 12. | Lack of information | 12.12 | 17.65 | 20.00 | 15.00 | 1.98 |

observed in the vegetables-pulses crop combination. Increased NF returns can be attributed to expenditure savings due to local inputs and additional revenue from intercrops. Mixed cropping helped to make more efficient use of the farm area than solo crop cultivation to further increase the net profit, in addition to increasing the variety of available crops at different times during the growing season. The results were supported by the same study undertaken by Chandel et al. (2021) which stated that the REE was 11.80 to 21.55% higher in all the crop combination under the SPNF as compared to the CF system.

## Problems Faced by the Natural Farmers

There are constraints when it comes to any development process. Likewise, there are several constraints regarding natural farming, which were faced by the concerned natural farmers of Solan district. Some of the main constraints include unfair price in the market, irrigation facilities, lack of specialized markets for the produce, high wage rates, lack of training facilities, etc. For examination of constraints, the Garrett's ranking technique was used. It must also be noted that these limitations have been aimed at the response of all the sample farmers. **Table 18** shows the constraints faced by various farm categories.

### Chi-Squared Test

An effort was made to examine the problems between different farm categories in the field of production and marketing. The chi-squared tests have been performed to check if the problems are specified by farm category or are independent of the farm

**TABLE 19 |** Farmers' perceptions and problems faced by NF growers in the study area.

| Sr. no. | Factors | Garret score | Percent | Rank |
|---|---|---|---|---|
| 1 | Labor intensive farming | 3,714 | 37.14 | I |
| 2 | Higher wage rate | 3,624 | 36.24 | II |
| 3 | Non-availability of specialized market | 3,552 | 35.52 | III |
| 4 | Shortage of skilled labor | 3,275 | 32.75 | IV |
| 5 | Lack of knowledge for package of practices | 3,244 | 32.44 | V |
| 6 | Consumer awareness about NF produce | 3,087 | 30.87 | VI |
| 7 | Lack of extension facilities | 2,995 | 29.95 | VII |
| 8 | Unfair price for produce in the market | 2,861 | 28.61 | VIII |
| 9 | Lack of transport facilities | 2,823 | 28.23 | IX |
| 10 | Lack of Irrigation facility | 2,775 | 27.75 | X |
| 11 | Inadequate training facilities | 2,737 | 27.37 | XI |
| 12 | Lack of market information | 2,583 | 25.83 | XII |
| 13 | Wholesalers not taking consent while selling | 2,585 | 25.85 | XIII |
| 14 | Higher commission | 2,531 | 25.31 | XIV |

category. As prices differ greatly, producers have had problems with production and marketing due to high wage levels, lack of technical awareness, lack of safe plant material, and lack of irrigation and storage facilities. These concerns were categorized in two subgroups: production issues and marketing issues.

It was observed from **Table 18** that among the production problems, shortage of skilled labor, higher wage rate, non-availability at peak operation time, and inadequate training facilities were found statistically significant. It showed significant differences between the different farm categories. In case of marketing problems, non-availability of specialized markets, lack of transport facility, and fair price in the market were found statistically significant. It showed that these problems were faced by all the farm categories.

### Garrett's Ranking Technique

The various problems faced by the farmers are shown in **Table 19**.

The Garrett's ranking system was used in this analysis, using the ranks attained by each problem to assess the most serious and the least serious problems. The major problems faced by the farmers were labor intensive (I) followed by higher wage rate (II), non-availability of specialized market (III), shortage of skilled labor (IV), knowledge of package of practices (V), consumer awareness about NF produce (VI), lack of extension facilities (VII), unfair price for produce in the market (VIII), etc. Other common problems include lack of transport facilities, lack of irrigation facilities, etc.

## CONCLUSION

Intercropping with leguminous crops is considered as one of the most important components of natural farming as it increases crop productivity and soil fertility through the atmospheric nitrogen fixation. The results revealed that farmers witnessed a drop in per hectare cost of production and profitable yield for their crops as well. The farmers were pleased that natural farming is both environmentally friendly and extremely cost-effective. The crop equivalent yield (CEY) under natural farming was highest in all the crop combinations as compared to conventional farming and ranged from 3.08 to 5.10% in Kharif season and 2.83 to 7.98% in all the crop combinations in Rabi season. In Kharif season, the percentage reduction in cost of cultivation under NF over the CF system ranged from 12.56 to 30.73, while in Rabi season, it ranged from 6.86 to 12.34. The gross returns under NF systems were highest in all the crop combinations as compared to CF systems. The maximum increase in gross returns was in vegetables crop combination in both the seasons. The relative economic efficiency (REE) was highest in all the crop combinations under NF over CF system. Among the problems studied, shortage of skilled labor, higher wage rate, non-availability at peak operation time, inadequate training facilities, non-availability of specialized markets, lack of transport facility, and fair price in the market were found statistically significant. It showed significant differences between the different farm categories. The analysis showed that the natural farming system provides relatively higher returns per hectare than the conventional farming system. Also, it was observed that the major problems faced by the farmers were labor intensive (I) followed by higher wage rate (II), non-availability of specialized market (III), shortage of skilled labor (IV), knowledge of package of practices (V), consumer awareness about NF produce (VI), lack of extension facilities (VII), unfair price for produce in the market (VIII), etc. Other common problems include lack of transport facilities, lack of irrigation facilities, etc. So, there is a need for the Department of Agriculture to take up effective measures to encourage natural farming through campaigns by educating the farmers about its importance. The government should also encourage higher premium prices and channels of green marketing for the boosting of natural crops. The farmers should focus more on the full application of the NF model on their farm fields and should know the best way to use these products, i.e., proper mulching techniques (acchadan), application of *jivamrit*, *ghanjivamrit*, *bijamrit*, *astras*, etc., in order to enhance productivity.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

## REFERENCES

Carrington, D. (2019). *EU Bans UK's Most-Used Pesticide Over Health and Environment Fears*. London: The Guardian.

Chandel, R. S., Gupta, M., Sharma, S., Sharma, P. L., Verma, S., and Chandel, A. (2021). Impact of Palekar's natural farming on farmers' economy in Himachal Pradesh. *Indian J. Ecol.* 48, 873–878.

Eliazer, N. A. R. L., Ravichandran, K., and Antony, U. (2019). The impact of the Green Revolution on indigenous crops of India. *J. Ethn. Food* 6, 1–11 doi: 10.1186/s42779-019-0011-9

Farrell, M. J. (1957). The measurement of productivity efficiency. *J. R. Stat. Soc. Ser*. 120, 153–290. doi: 10.2307/2343100

Francis, C. A. (1986). Distribution and importance of multiple cropping. *Agric. Syst.* 25, 238–240. doi: 10.1016/0308-521X(87)90024-2

Garrett, E. H., and Woodworth, R. S. (1969). *Statistics in Psychology and Education*. Vakils, Feffer and Simons Pvt. Ltd., Bombay.

Gomez, K. A., and Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research*, *2nd Edn*. New York, NY: John Wlley and Sons.

Khadse, A., and Rosset, P. M. (2019a). Zero Budget Natural Farming in India-from inception to institutionalization. *Agroecol. Sustain. Food Syst.* 8, 21–35. doi: 10.1080/21683565.2019.1608349

Khadse, A., and Rosset, P. M. (2019b). Zero budget natural farming in India from inception to institutionalization. *Agroecol. Sustain. Food Syst.* 4, 5–6.

Khadse, A., Rosset, P. M., Morales, H., and Ferguson, B. G. (2017). Taking agroecology to scale: the zero budget natural farming peasant movement in Karnataka, India. *J. Peasant Stud*. 45, 9–12. doi: 10.1080/03066150.2016.1276450

Menon, P., Deolalikar, A., and Bhaskar, A. (2008). *Comparisons of Hunger across States: India State Hunger Index*. International Food Policy Research Institute.

Ministry of Commerce (2021). *Agriculture in India: Information about Indian Agriculture and Its Importance*. Available online at: https://www.ibef.org/industry/agriculture-india.

Mishra, S. (2018). *Zero Budget Natural Farming: Are This and Similar Practices The Answers*. Nabakrushna Choudhury Centre for Development Studies, Bhubaneswar.

Palekar (2005). *The Philosophy of Spiritual Farming Amravati: Zero Budget Natural Farming Research, Development and Extension Movement*. Amravati.

Pearson, K. (1900). On the Criterion that a given system of deviation from the probable in the case of a co-related system of variables is such that it can be reasonably suppose to have arisen from random sampling. *Philos. Mag. Ser*. 50, 157–175. doi: 10.1080/14786440009463897

Sebby, K. (2010). *The Green Revolution of the (1960)'s and Its Impact on Small Farmers in India*. Environmental Studies Undergraduate Student Thesis. Available online at: https://digitalcommons.unl.edu/envstudtheses/10

Tripathi, S., and Tauseef, S. (2018). *Zero Budget Natural Farming, for the Sustainable Development Goals*. Andhra Pradesh.

Vashishat, R. K., Laishram, C., and Sharma, S. (2021). Problems and factors affecting adoption of natural farming in Sirmaur District of Himachal Pradesh. *Indian J. Ecol.* 48, 944–949.

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 07 December 2022
DOI 10.3389/fsufs.2022.1001367

# Cropping system intensification for smallholder farmers in coastal zone of West Bengal, India: A socio-economic evaluation

Subhasis Mandal[1*†], Sukanta Kumar Sarangi[2†], M. Mainuddin[3†], K. K. Mahanta[4], Uttam Kumar Mandal[5], D. Burman[6], S. Digar[6], P. C. Sharma[1] and B. Maji[6]

[1]Division of Social Science Research, ICAR-Central Soil Salinity Research Institute, Karnal, India, [2]Department of Agronomy, ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning, India, [3]Basin Management Outcomes Group, Water Resource Management Program, Commonwealth Scientific and Industrial Research Organisation Land and Water, Canberra, ACT, Australia, [4]Department of Soil and Water Conservation Engineering, ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning, India, [5]Department of Soil Science, ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning, India, [6]ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning, India

**Introduction:** It is estimated that five out of six farms in the world are operating less than two hectares of land, called smallholder farmers, and they are producing over one third of the global food. Cropping system intensification research and interventions at farmers' fields could be one of the ways to improve the prevailing cropping systems. Understanding socio-economic issues are important for the successful implementation of improved or new cropping systems and for increasing farmers' income in the coastal zone of the Ganges delta. A socio-economic evaluation study was carried out to understand how far the suggested cropping options were feasible to smallholder farmers in the coastal zone; quantify the benefits due to the adoption of new cropping systems; how far those options were socio-economically suitable for the targeted smallholder farmers; and to identify the key factors that might be affecting the out-scaling of the evolved options to a larger group of farmers.

**Methods:** Baseline and endline surveys were conducted with 90 farmers before and after the demonstration of various cropping systems at farmers' fields. Techno-economic suitability of new crops and management options were evaluated through accounting benefits of adoption and identifying various constraints in adoption. Behavioral analysis was carried out to identify factors affecting large-scale adoption of the new/improved cropping systems evolved.

**Results and discussion:** The socio-economic survey quantified the increase in cropping intensity higher than the baseline level (123–142%) and reduced the *rabi* (winter/dry) season fallow area by 30–35%. The study identified farmers' preferred interventions were low-cost drip irrigation and mulching, zero-tillage (ZT) potato with straw mulching, improving soil quality with lime and green

Check for updates

OPEN ACCESS

EDITED BY
Tapan Kumar Nath,
University of Nottingham Malaysia Campus, Malaysia

REVIEWED BY
Souvik Ghosh,
Visva-Bharati University, India
Arun Pandit,
Central Inland Fisheries Research Institute (ICAR), India

*CORRESPONDENCE
Subhasis Mandal
subhasis2006@gmail.com

†These authors have contributed equally to this work

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 23 July 2022
ACCEPTED 19 October 2022
PUBLISHED 07 December 2022

CITATION
Mandal S, Sarangi SK, Mainuddin M, Mahanta KK, Mandal UK, Burman D, Digar S, Sharma PC and Maji B (2022) Cropping system intensification for smallholder farmers in coastal zone of West Bengal, India: A socio-economic evaluation.
*Front. Sustain. Food Syst.* 6:1001367.
doi: 10.3389/fsufs.2022.1001367

manuring, and vegetable-based cropping systems interventions. Although the economics of the evolved cropping systems were favorable, however, availability of freshwater stored in ponds/canals, and income from on and off-farm were the most important factors determining the adoption of new systems on a larger scale.

KEYWORDS

**cropping systems, coastal zone, agricultural income, socio-economic impact, technology adoption**

## Introduction

Globally, around 40% of the world's population lives within 100 km of coastline (Small and Nicholls, 2003; Kummu et al., 2016) and most of the largest urban concentrations are on the coast. The current coastal urban population of 220 million is projected to almost double in the next 20–30 years (FAO., 1998). Indian agriculture comprises 263.1 million farmers, 138 million operational holdings, farming on 160 million ha, with an average holding size of 1.15 ha (Govt. of India, 2020). Coastal Zone in India covers 7,516 km of coastline (SAC (Space Applications Centre), 1992), spread over 9 States, 2 Union Territories, 2 Island Territories; 77 districts (69 on the mainland and others in the Island system), housing 171 million population (14.2 percent of India). The geographical area of the Ganges delta which is shared with neighboring Bangladesh is one of the most important parts of the coastal zone in India, and has great significance for food security, biodiversity conservation, and fisheries production (Mainuddin et al., 2019; Mandal et al., 2020). The region is endowed with rich and diverse natural resources. Agriculture, horticulture, aquaculture, animal husbandry, etc. are the primary livelihoods of the people living in the coastal zones of India but the productivity of all these sectors is much below the national average because of various constraints related to soil, water, and climate (Bandyopadhyay et al., 2011; Mandal et al., 2013; Burman et al., 2015). The socio-economic status of the population dwelling in coastal areas is also much below as compared to the national level. The Coastal region is likely to face severe challenges in the future due to the rise in sea levels following global warming (Mandal et al., 2019a,b; Mainuddin and Kirby, 2021; Mainuddin et al., 2021a). The management of the natural resources and sustenance of ecology in the coastal region are some of the vital issues in this Ganges delta. Major challenges to achieving the self-reliance goal for the region could be, managing the natural resources of the smallholder farmers with gainful engagement, uses of critical resources (land and water) sustainably, reducing the farmers' distress by scientific input management or compensating through direct benefit transfer schemes, managing environmental risk, enhancing marketable surplus through grassroots level institutional innovations (like farmers organization) and linking farmers to markets. The Human Development Report (Govt. of West Bengal, 2009) highlighted that the agriculture in the coastal district is turning out to be gradually un-remunerative, and observed a declining trend in the agricultural workforce and often leading to poverty due to high dependence on the primary sector. Despite having many constraints, farming in coastal regions has good potential to enhance farmers' income through the scientific intervention of soil and water resources (Mandal et al., 2015a, 2018b).

One of the ways to improve the agriculture-dependent livelihoods conditions of farmers can be achieved through the promotion of viable cropping systems suitable for the smallholder farmers in the region (Mandal et al., 2017; Ray et al., 2018, 2020; Bell et al., 2019; Remesan et al., 2021). Agricultural production systems evolved around the principles of sustainable intensification to increase agricultural productivity with minimum environmental and social trade-offs. System intensification is now widely recognized as an important pathway to food security in developing countries (Garnett et al., 2013). Farmers' decision of choosing the cropping system in the coastal region is influenced by several biotic and abiotic factors including waterlogging, salinity, lack of good quality irrigation water, capital inadequacy, agricultural risk, and uncertainties in production systems (Kabir et al., 2017a, 2018; Krupnik et al., 2017; Aravindakshan et al., 2018; Hasan and Kumar, 2020). Often, despite having the available options, farmers sacrifice the expected higher return through an intensive cropping system due to these prevailing multiple stressors as the resource-poor farmers prefer to remain safe than sorry in an unforeseen situation (Mandal et al., 2019a,b). Several suitable cropping system options for coastal Bangladesh were identified, but their adoption was challenged by factors such as limited access to stress-tolerant varieties, extension services, and affordable agricultural credit, combined with high production costs, variability in crop yields, and output prices (Kabir et al., 2017b; Mandal et al., 2018a). Agricultural development policies in the coastal region have been emphasized mainly on two strategies, developing salt-tolerant crop varieties and utilizing rainwater harvested in canal systems or creation of on-farm reservoirs (Sharma et al., 2016; Mandal et al., 2017; Kumar and Sharma, 2020). *Kahrif* (rainy/wet) season is extensively cultivated but most of the land in *rabi* (winter/dry) season remained fallow due to a shortage of good quality irrigation water and therefore targeted by the policy planners to achieve higher cropping system intensification (Aravindakshan et al., 2018; Mainuddin et al., 2019; Yadav et al., 2020). Therefore, enhancing crop production, particularly by growing a crop in the typically-fallow dry season is a key strategy that has a direct positive impact on alleviating poverty in the Ganges delta region (Mainuddin et al., 2021b), and productivity in the coastal zone can be increased by several folds (Bhattacharya et al., 2015; Ritu et al., 2015; Saha et al., 2015).

Key challenges for achieving higher cropping intensifications are: excess water in *kharif* season causing a waterlogged situation; availability of less water (good quality) during *rabi* season (dry) resulting in salinity building up on the soil surface that limits the number of choices of crops (Mandal et al., 2011a; Humphreys et al., 2015); the trade-off between off-farm and on-farm income often becomes unfavorable to agriculture due to low return; in coastal saline conditions, particularly in *rabi* season cropping becomes more risky and uncertain that leads to large areas under fallow land. Historical records indicated that in the Delta region on average, 4.29 cyclones originated annually in the Bay of Bengal, constituting only 5–6% of the global total and these are very severe among all cyclones (Paul, 2009; Alam and Dominey-Howes, 2014; Paul and Rashid, 2017). Climate fluctuations are likely to alter the profitability and suitability of cropping choices and patterns across the Delta region (Yu et al., 2010) which are major challenges to farming communities. Also, the climate change projections indicated future spatio-temporal challenges for yield stability over time, especially for less diversified agricultural systems (Berzsenyi et al., 2000; Lin et al., 2011; Urruty et al., 2016), hence stressed the importance of cropping system research and adoption by the smallholder farmers in the region. All these also influence large-scale seasonal migration for alternative livelihoods; and poor road infrastructure and market linkages lead to higher income instability (Tur-Cardona et al., 2018; Bell et al., 2019; Mandal et al., 2019a). Research recommendations on cropping system intensification in coastal zones are often drawn from the improved yields and return of the crops, based on researchers' managed experimental findings (Dillon and Hardaker, 1993; Childs and Kiawu, 2009; Neumann et al., 2010; Fisher, 2015), ignoring the socio-economic suitability of the evolved options. Often recommended new cropping systems require higher investment to turn the options into practice or return to scale may not be as attractive or easy to adopt, as it is perceived to be, becomes a key determinant factor to affect smallholder farmers' decisions. Thus, analyzing farmers' preferences and desires are the pre-requisite for consideration in policy decision for its success (Dolinska, 2017; Aravindakshan et al., 2018). Farmers' preferences for alternate cropping options are studied by quantitative ranking procedures (Soltanmohammadi et al., 2010) or qualitative focus groups (Mekoya et al., 2008). The extent to fulfill the household goals depends on managerial skills and also considerable luck with the weather and other uncertain environmental factors without any control of the households (Anderson and Dillon, 1992). While recommending the strategies, the cumulative interaction of the biophysical and socio-economic elements over time needs to be considered (Norman et al., 1981; Pingali et al., 1987; Walker and Ryan, 1990). Socio-economic studies can highlight the enabling strategies required for the out-scaling of such recommended package of practices in the targeted areas. Therefore, along with the experimental findings, it is imperative to study the socio-economic suitability of the new cropping systems that are suggested. In view of these issues, on-farm research on cropping system intensification in the salt-affected coastal zones of West Bengal, India was implemented with the objective of evolving new cropping systems or improving the existing cropping system suitable for the smallholder farmers in the region. This socio-economic impact analysis was carried out with the objectives of (1) understanding the existing cropping practices and comparing those to the proposed change that was evolved/ improved through the cropping system intensification research project; (2) identifying various socio-economic factors that determine the adoption of new/evolved cropping system options; (3) understanding various knowledge gained by the farmers through demonstration of cropping systems at farmers' fields and their potential use; and (4) how far such options were financially feasible to out-scale to a large number of farmers in the coastal saline zone through public investment.

## Materials and methods

### Study area and site description

The study area is located on Gosaba island of South 24 Parganas district in the Ganges delta. The coastal zone of the Ganges Delta in India, known as *Sundarbans,* is comprised of a geographical area of 9,630 km$^2$ spread over 102 islands, and among these 54 islands have human settlements. The area under human inhabitation is 4,444 km$^2$, falling under two coastal districts of West Bengal, South and North 24 Parganas. The Indian *Sundarban* region (Indian part of the Ganges delta) accounts for 33% (0.44 million ha) of the total area (1.33 million ha) of these two coastal districts. Out of the total population of the *Sundarban* region (4.43 million), almost 74% are from South 24 Parganas and the rest (26%) are from North 24 Parganas district (Census of India, 2011). Among the total workers (1.67 million) in *Sundarbans*, around one-fifth (20%) are agricultural laborers and 12% are cultivators, directly thriving on agriculture. The economy of coastal areas of West Bengal is mainly dependent on agriculture and allied activities, comprising crop cultivation, fisheries, animals, and forestry, which influences the livelihoods

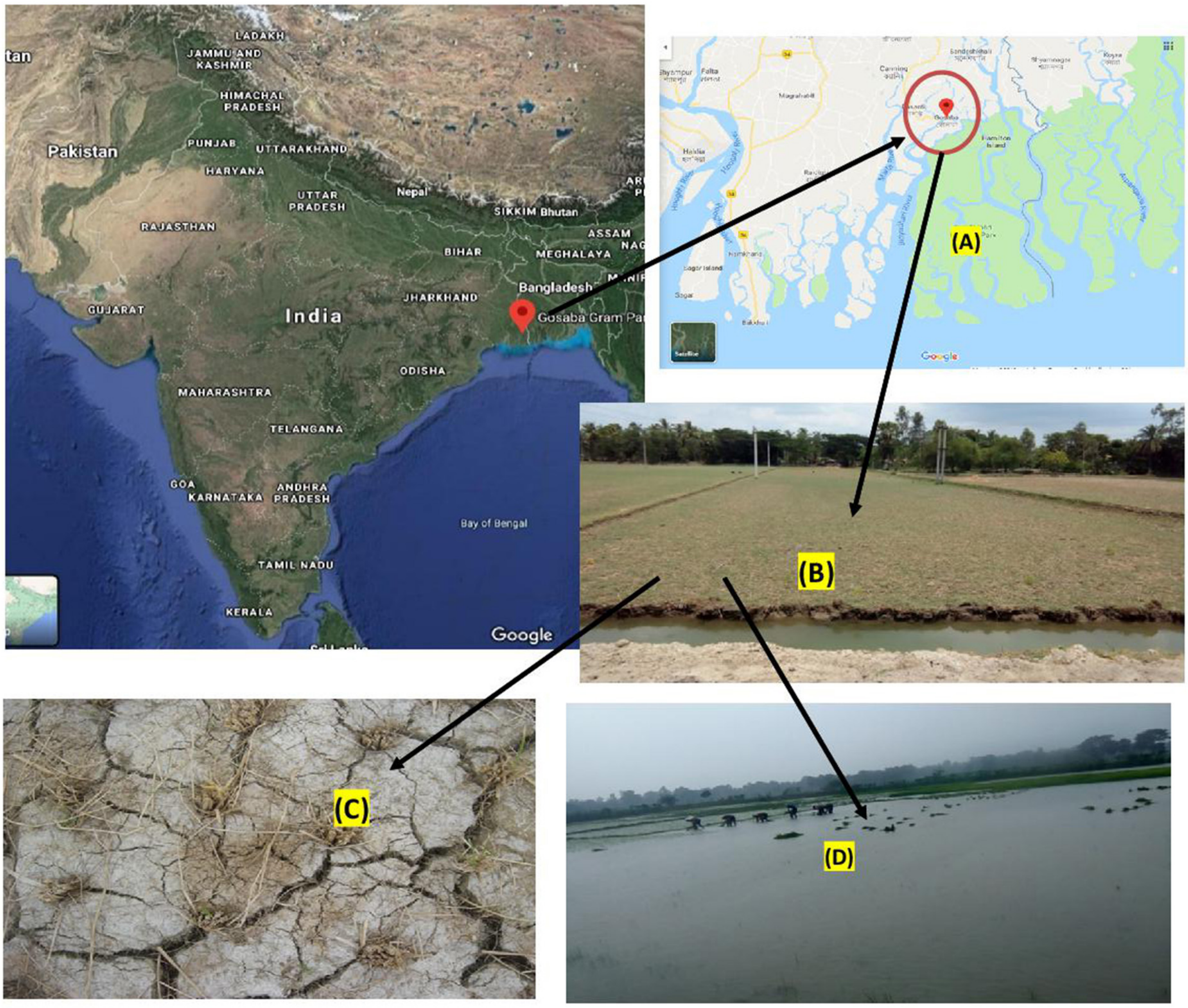


FIGURE 1
Location of the study area **(A)** and the physiography **(B)** of the coastal zone during *rabi (dry/winter)* **(C)** and *kharif (wet/rainy)* season **(D)**.

of millions of rural households in the region. The cropping system in coastal West Bengal is dominated by *kharif* rice (86%) followed by *rabi* rice, and vegetables in main fields and in homestead lands. Homestead production system is an integral part of daily household activities and produces food (fruits, vegetables, fish, and livestock) for household consumption and contributes significantly toward meeting daily food and nutrition requirements and generates cash income when surplus is produced on a limited scale (Mandal et al., 2015b; Goswami et al., 2021). Drainage congestion leads to prolonged waterlogging is one of the major issues for coastal agriculture in the coastal area (Ghosh and Mistri, 2020). Agricultural operation on the island is primarily rain-fed as the availability of groundwater in the coastal zone is extremely limited and often withdrawal becomes uneconomical for use in agricultural production. Supplementary irrigation depends on the collection of rainwater from the monsoon season in ponds and canals. The rainwater harvested and stored in ponds or canals is normally used for irrigation during the *rabi* season. A multidisciplinary research project on improving cropping system intensification was carried out in this coastal saline zone of West Bengal, India from 2016 to 2020 (Figure 1). A number of field experiments (8) were undertaken at the farmers' field under the supervision of a team of agro-scientists covering experts from agronomy, soil science, soil and water conservation specialist, agricultural engineers and economist (ACIAR, 2020). Keeping in view of resource availability of smallholder farmers and the actual challenges of managing soil and water, different cropping system experiments were conducted. This ensured the creation of several options for the farmers so that they can choose the best combination of crops as per their needs and suitable to their resource base.

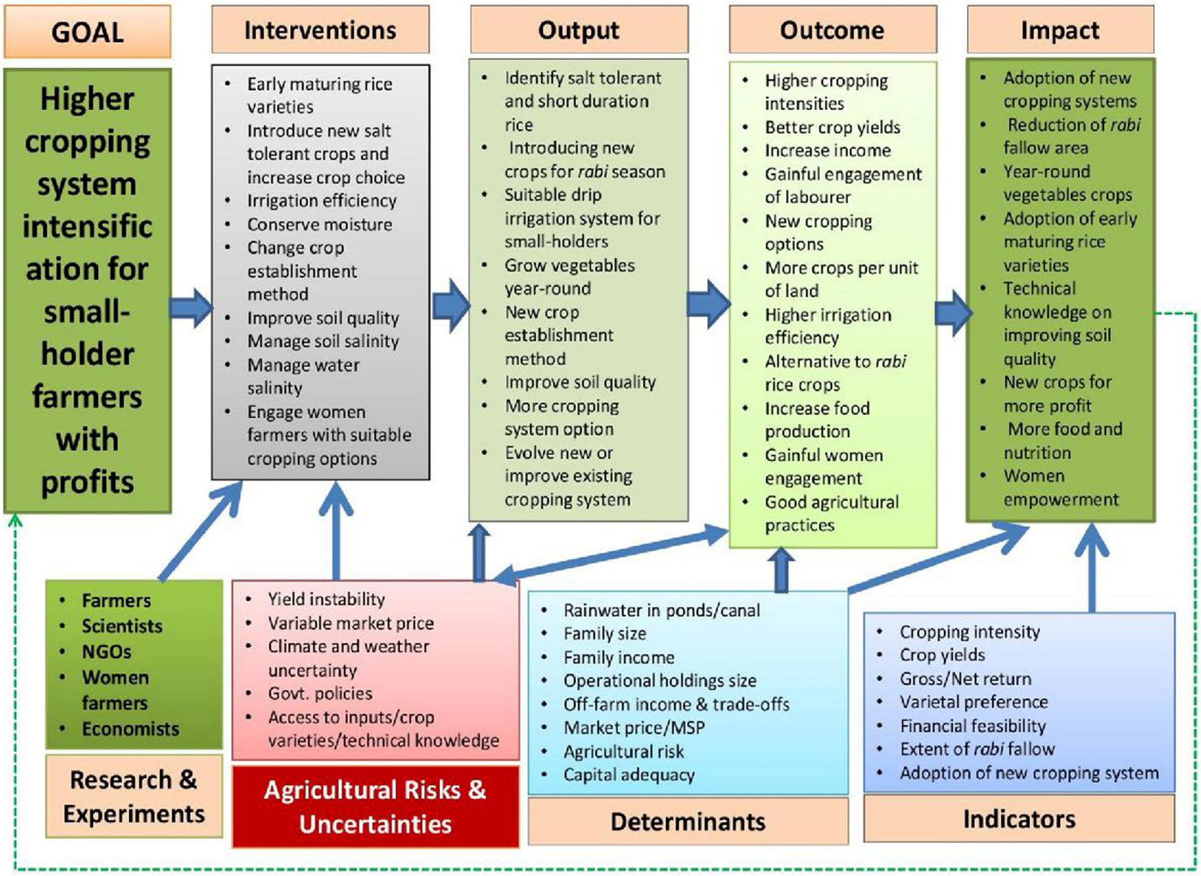


FIGURE 2
Framework for cropping system intensification interventions and outcomes.

## Framework for cropping system intensification interventions and outcome

Smallholder farmers with an operational area below two hectares of land are the most dominant category of farmers in the coastal zone of West Bengal, India (Supplementary Figure A1 in Annexure I) and they manage their land with limited available resources (land, good quality water, and finance). Keeping in view the limited availability of freshwater water resources and the coastal stressed environment (salt-affected soil), various field experiments were carried out to improve the cropping system intensification with the goal to enhance agricultural income. Research experiments were initiated with active consultation of the farmers to prioritize the problems and to find a need-based solution to facilitate the easy adoption of new or improved cropping systems generated through these interventions. Possible agricultural risks and uncertainty like salinity and instability of crop yield due to climatic factors were kept in mind to design these cropping intensification experiments. Key strategic research interventions promoted were, introducing early maturing rice varieties aligning with farmers' preferences, introducing salt-tolerant crop varieties (rice and non-rice), increasing irrigation water use efficiencies through drip irrigation systems, water conservation, and utilizing the field water for crop production, improving soil and water quality through applying amendments and green manuring and finally keeping in view of the activities and role of women farmers in managing the cropping systems. The outcomes of the experiments were expected to be affected by several determinants (bio-physical and socio-economic) during the experimental period and post-project period. Socio-economic factors were identified and considered while conducting the socio-economic impact study. All these factors affecting the adoption of the cropping systems were analyzed. The conceptual framework of the study is given in Figure 2.

## Data source, baseline, and end-line surveys

A baseline survey was conducted to collect primary data during 2017–2018 from 90 farmers in the study village, *Sonagaon* under the Gosaba community development block of South 24 Parganas district, West Bengal. Almost all farmers in the area was belonging to smallholder categories, and random sampling was followed for the selection of the farmers. The list of households dwelling in the village was obtained from the local government office (called *gram panchayat*) and the sample farmers were drawn randomly. Data were collected through a personal interview, interviewing key informants, and conducting focus group discussion (FGD) with the farmers by using a pre-structured and tested survey schedule. Responses of farmers were recorded to understand their experiences/opinions on cropping intensification interventions while they managed farmlands under scientists' supervision and also by themselves ICAR-CSSRI CSI4CZ (2020). Detailed information on farm size, educational status, occupation, cropping systems practiced, cropping pattern, income sources, costs and returns of crops grown, production and marketable surplus of crops, selling of crops, agricultural risks, and constraints in farming were collected. Baseline information on socio-economic characteristics and economics of cropping practices of the farmers was analyzed by employing farm budgeting analysis.

During and after 4 years, the project interventions were spread over a large number of farmers but the end-line survey was conducted during 2020–2021 from the same 90 farmers to understand the impact of interventions. To understand the farmers' response/perception, feedback surveys of the farmers on all different interventions made through the project period was also conducted. The primary survey was conducted through a personal interview based on a pre-structured tested survey schedule. Also, some qualitative information was collected through different ways such as FGDs (15–20 farmers in each group) and telephonic interviews with the key informants. The baseline and end-line survey data were compared (before and after the project) to analyze the socio-economic impact of the various interventions made during the project. Changes in cropping area at the farm households level were recorded due to the adoption of the cropping systems as compared to the baseline situation. The socio-economic impact assessment also included identifying new knowledge/experience gained by the farmers during the active demonstration of the experiments and possible changes that they might be adopting in their existing cultivation practices. The study also recorded key knowledge gained that could be helpful for addressing the critical constraints and have implications for larger policy perspectives, relevant to the coastal zone as a whole. Besides, women folk also plays a very active role in almost all the farming operation in the coastal zone in West Bengal, India, therefore separate FGDs (4 number) were conducted with the women farmers. During each FGDs 8–10 woman farmers were invited to discuss their role and activities in the farming operation in the existing practices, likely changes in the workload while adopting the new cropping systems, and their opinion regarding the adoption of new interventions/options suggested.

## Economics of cropping systems

The economics of the crops has been analyzed through farm budget analysis, following the norms of cost of cultivation methods of Commission for Agricultural Costs and Prices (Govt. of India, 2008). Costs components included, input costs incurred on seed, fertilizers, irrigation, human labor (hired and own) required for all activities (land preparation, sowing, applying irrigation/pesticides/fertilizers, intercultural operation, harvesting, etc), machine labor (mainly power tiller), fertilizers, organic manure/compost, irrigation charges, pesticides (insecticides/fungicides/herbicides), interest rate on working capital as the opportunity cost of capital expenditure (maximum 6 months for annual crops), depreciation charges, and miscellaneous (like watch and ward, unforeseen expenditures, etc) expenses. Cost of labor has been calculated based on open market prices of labor hiring charges and the cost of family labor has been imputed with same rate. Gross return has been calculated based on the gross value of output (production multiplied by farm-gate prices) plus the value of by-product. Net return has been calculated by deducting the total cost of cultivation from the gross value of output.

## Preference analysis of kharif rice varieties

Rice in both *kharif* and *rabi* seasons is the main crop in the coastal areas. One of the key strategies to achieve higher cropping system intensification was to promote suitable short-duration *kharif* rice varieties so that fields will be ready early, facilitating intensive *rabi* season cultivation, then alternate to *rabi* rice. Thus, ranking analysis for varietal preference and adoption behavior of farmers was carried out for *kharif* rice only. Varietal preferences were largely dependent on several criteria, varietal attributes, and the expectations of farmers (Burman et al., 2018). Farmers' choice of a particular rice variety was influenced by several attributes like salinity tolerance, the capacity to withstand waterlogging (plant height), tolerance to pests and diseases, grain and straw quality, tolerance to lodging, and duration of the crop. To rank various preference criteria, the rank-based quotient (RBQ) analysis was employed (Burman et al., 2018). The criteria used by farmers for their selection of the most preferred variety were listed first, and then they were asked to rank those criteria according to their individual priority on a scale of 1–5. The most preferred criteria were ranked as 1, and the least preferred as 5. The analysis allowed the ranking of farmers' preferences based on RBQ values. The RBQ is a problem identification technique, mathematically presented as follows:

$$RBQ = \sum\nolimits_{j=1}^{n} \frac{fi\,(n+1-i)*100}{N*n}$$

where $N$ = total number of farmers, $n$ = total number of ranks (there are five ranks, $n$ = 5), $i$ = the rank for which the RBQ is calculated (for a problem), and $f$ = number of farmers reporting the rank *i* (for the problem). This analysis was carried out to prioritize the rice varieties to be grown as per the farmers' preferences.

## Identification of constraints

Agricultural production systems for smallholder farmers are affected by different social and economic factors which determine the adoption behavior of new technologies (Mandal et al., 2019b). A detailed discussion was held with the farmers to identify the critical constraints experienced by the farmers. These factors were of different types such as environmental constraints (soil and water salinity, water availability); institutional (input availability in time and quality, access to technical know-how,); and economic constraints (input cost, access to markets, capital adequacy, agricultural production, and marketing risks). Farmers were asked to respond to a list of all these constraints and the percentage of farmers who responded to each of these constraints was recorded. Likely solutions or options to address these constraints were also discussed and different new knowledge gained from the project interventions might be useful to mitigate those problems, was highlighted.

## Statistical analysis for mean differences

A paired '*t*' test was applied to compare the changes in cropping area, cost, and return for the cropping systems before and after the interventions made through this project. The hypothesis was:

$H_0$ = area under crops, cost, or return structures was remaining the same before and after the interventions.

$H_1$ = area under crops, cost or return structures were different before and after the interventions.

The value of '*t*' was calculated as below:

$$t = \frac{\bar{d}}{SE(\bar{d})}$$

and

$$SE\left(\bar{d}\right) = \frac{s_d}{\sqrt{n}}$$

where, $\bar{d}$ = Mean difference in area, cost or return before and after interventions $SE(\bar{d})$ = Standard error of mean area, cost, or return before and after the interventions.

$s_d$ = Standard deviation of mean area, cost, or return before and after the interventions,

$n$ = number of observations on area, cost, or return before and after the interventions.

## Factors affecting adoption of new/improved cropping systems

Adoption behavior and decision-making of farmers to adopt new/improved cropping systems depends on several socio-economic factors. Various socio-economic factors that may determine the adoption of new/improved interventions were analyzed through behavioral analysis. The expected sign and justification for the inclusion of these variables area explained in Supplementary Table A1 in Annexure II. The cropping intensity of individual farm households' level was estimated during baseline and endline surveys along with different key socio-economic parameters that were likely to affect farmers' decision-making. Achieving higher cropping intensity as compared to the estimated baseline level of cropping intensity (up to 142%) by the individual farm households, after the project intervention, was desirable. The cropping system experiments were conducted in the fields of a few farmers in a small part of their lands and based on the performance of crops, different cropping systems were promoted to other farmers and subsequently many of them adopted the new cropping systems, for which their cropping intensities increased. Therefore, farmers' who practiced the new cropping systems and achieved the cropping intensities (including the farmers who had provided part of their land for experiments) above the baseline level (142%) were assigned 1 in the binary dependent variable (*Zi*), and 0, otherwise. The behavioral analysis was done using a binary logistic regression model to identify the different key determinants of the adoption of new cropping systems toward achieving higher cropping intensity in the coastal zone.

The framework for binary logistic regression is specified as:

$$\mathrm{Yi} = \mathrm{g}\ (\mathrm{Z_i}) \tag{1}$$

Here $Z_i$ is an index variable (or vector of $X_{ki}$ independent attributes) and formally can be written as:

$$\mathrm{Z_i} = \ln\left(\frac{\mathrm{P_i}}{1-\mathrm{P_i}}\right) = \alpha + \beta_{\mathrm{k}}\mathrm{X_{Ki}} \tag{2}$$

$$P_i = F\left(Z_i\right) = F\left(X_i\right) = \frac{1}{1+e^{-z_i}} \tag{3}$$

Once this equation is estimated, *P* can be calculated as:

$$= \frac{1}{1+e^{-(\alpha+\beta_k X_{ki})}} \tag{4}$$

where,

$Y_i$ = Status of farmers ($Y$ = 1 for farmer who has achieved higher cropping intensity than baseline average and 0 otherwise);

$Z_i$ = An underlying and unobserved response for the ith farmer. When $Z$ exceeds threshold $Z^*$, the farmer takes the decision to adopt, otherwise not.

$X_{ki}$ = $k$th explanatory variable for the ith farmer;

$i = 1,2,3, \ldots, N$, where $N$ is the number of farmers;

$K = 1,2,3,\ldots, M$, where $M$ is the total number of explanatory variables;

$\alpha$ = constant;

$\beta$ = unknown parameters, and e denotes the base of natural logarithim with a value ∼2.718.

The variables included in the model, were:

*Zi*—a binary variable, 1 = farmer achieved higher cropping intensity as compared to baseline value (142%), 0 otherwise,

$X_1$–Operational holding size (average in ha household$^{-1}$, excluding homestead area),

$X_2$–Homestead area (average in ha household$^{-1}$),

$X_3$–Income from agriculture (in ₹ year$^{-1}$ household$^{-1}$),

$X_4$–Off-farm income (in ₹ year$^{-1}$ household$^{-1}$),

$X_5$–Number of adult male (Number household$^{-1}$),

$X_6$–Number of adult female (Number household$^{-1}$),

$X_7$–Number of perennial ponds (Number of ponds household$^{-1}$ available having water for 9 or more months),

$X_8$–Primary occupation (If agriculture = 1, 0 otherwise),

$X_9$–Age of respondents (Years in number),

$X_{10}$–Status of education (Number of years of schooling), and

$X_{11}$–Distance of nearest market fields (in km),

All these variables were expected to influence, either positively or negatively, farmers' decision to adopt new/improved cropping systems for enhancing their level of cropping intensification and farm income.

## Results and discussion

### Socio-economic status of farmers and economics of cropping system practices

Most farmers (98%) in the study area belonged to the marginal categories and operated less than a hectare of land (average of 0.48 ha). The livelihood pattern of the farmers was dominated by agriculture as the primary occupation (44% of the farmers), but the agricultural income was meager (around ₹21,000 hh$^{-1}$ year$^{-1}$), not sufficient for the families, therefore migration (32%) to other places for the search of alternative livelihoods was quite common. The cropping pattern was dominated by *kharif* rice (86% of gross cropped area) followed by *rabi* rice and a number of vegetables in small plots (mostly as mixed cropped plots). The Homestead production system was (average of 0.07 ha) an integral part of their production system, having a good contribution in terms of providing household food security to the farmers. The baseline cropping intensity was estimated to be 123 and 142% in the study area, with and without the inclusion of homestead area, respectively (Supplementary Table A2 in Annexure II).

Crop selection is a key management decision to improve yield stability over time in the coastal region of Bangladesh to improve the livelihoods condition of smallholder farmers, also ascertained by Carcedo et al. (2022). The interventions on cropping system intensification successfully evolved new or improved the existing cropping systems. A number of cropping system options were found feasible to increase the farmer's income from agriculture as compared to the existing cropping system. Dominant cropping systems were *kharif* rice-fallow, *kharif* rice-*rabi* rice, *kharif* rice-mixed vegetables, *kharif*-rice-potato (ridge) and homestead production system. Based on the experiments, cropping systems such as *kharif* rice-green gram, *kharif* rice-ZT (zero-tillage) potato, *kharif* rice-ZT potato-green gram, *kharif* rice-ridge potato, *kharif* rice-maize, and *kharif* rice-vegetables were suggested. Besides, the vegetable–vegetable–vegetable cropping system was also evolved by using solar-powered drip irrigation systems (Table 1, also Supplementary Tables A3, A4 in Annexure II). The most profitable cropping system was *kharif* rice-ZT-potato (output–input ratio 2.33), followed by *kharif* rice-vegetables (2.31), *kharif* rice-ZT potato-green gram (2.28), *kharif* rice-green gram (1.82), *kharif* rice-maize (1.71), *kharif* rice-ridge potato (1.61) and *kharif* rice-fallow (1.36). In terms of net return, *kharif*-rice-ZT potato-green gram cropping system provided the highest profitability (₹2,05,079 ha$^{-1}$), followed by *kharif* rice-ZT potato (₹1,62,290) and vegetables–vegetables under solar drip system (₹20,059 for 1,000 m$^2$ area). All the evolved cropping systems provided higher profitability as compared to the existing cropping systems (Mandal et al., 2020). Besides, the proposed cropping system intensification has the potential to increase the cropping intensity to 200–300% in the study area as compared to the existing 123–142%. Alam et al. (2021) also concluded in a study in coastal Bangladesh that the crop diversification in the existing rice-based (boro) cropping system with the introduction of the high-yielding potato, cucumber, and *T*. Aus rice, improved the system productivity, profitability, and sustainability in terms of higher gross margin (by 74%), net return (double) and benefit-cost ratio (BCR) (1.69 vs. 1.44). The improved cropping system increased the gross return by 2,666 US$ ha$^{-1}$ (49%) and net return by 1,616 US$ ha$^{-1}$ (double) as well as higher BCR (1.69) as compared to the existing system.

### Preference analysis of kharif rice varieties

The preference analysis was done after *kharif* rice harvest to understand the key attributes of rice preferred by the farmers. This ranking analysis was carried out with 20 farmers who participated in the rice varietal trials. Ranking analysis through RBQ score indicated yield was the major factor to choose a rice (*kharif* season) variety followed by resistance to lodging, duration of crops, capacity to withstand waterlogged (even submergence sometimes) situation or plant height, pest and disease resistance, quality of

TABLE 1 Cropping system intensifications and profitability in coastal zone of West Bengal, India.

| Cropping system | Total cost (₹ ha$^{-1}$) | Gross return (₹ ha$^{-1}$) | Net return (₹ ha$^{-1}$) | Output-input ratio |
|---|---|---|---|---|
| **Existing (farmers practices)** | | | | |
| *Kharif* rice-fallow | 38,393 | 52,350 | 13,957 | 1.36 |
| *Kharif* rice-*rabi* rice | 93,110 | 1,39,294 | 46,184 | 1.50 |
| *kharif* rice-ridge potato | 1,71,905 | 2,25,150 | 53,245 | 1.31 |
| **Evolved/improved (experimental plot)** | | | | |
| *Kharif* rice-fallow* | 38,046 | 80,835 | 42,789 | 2.12 |
| *Kharif* rice-green gram | 63,384 | 1,15,635 | 52,251 | 1.82 |
| *kharif* rice-ridge potato | 1,59,824 | 2,57,415 | 97,591 | 1.61 |
| *Kharif* rice-ZT potato | 1,22,125 | 2,84,415 | 1,62,290 | 2.33 |
| *Kharif* rice-ZT potato-green gram | 1,60,171 | 3,65,250 | 2,05,079 | 2.28 |
| *Kharif* rice-maize | 95,031 | 1,62,278 | 67,247 | 1.71 |
| Vegetable-vegetable-vegetable through Solar drip irrigation system (for 1,000 m$^{-1}$)# | 15,360 | 35,419 | 20,059 | 2.31 |

**kharif* rice -fallow system was improved over the farmers' practices in terms of soil management (e.g., lime/rock phosphate application for acid sulfate soil management along with green manuring) and introducing early maturing/submergence/waterlogged tolerant rice variety.

#Average area under experimental mixed vegetables crop plot was 725 m$^2$ and the calculation is on the basis of 1,000 m$^2$, @ Rabi rice was not under experiments. Source: primary survey by authors (2017–2018 and 2018–2019). Adapted from Mandal et al. (2020). 1 USD = INR or ₹70 (approximately) as on January 2021.

straw, grain quality and tolerance to salinity (Table 2). Different motivation factors that influence farmers' decision or willingness to choose their varieties indicated that the farmers' decision to change a rice variety remained unchanged when the incremental yield was obtained to the extent of 15% (Mandal et al., 2016). Under a saline environment, the instability of yield was quite high and the farmers have a rational expectation, therefore, farmers' willingness to change a variety remained indifferent up to incremental yield by 15%. Keeping in mind these attributes preferred by the farmers, the rice varietal selections for the experiments were made, subsequently (for example, the *Amal-Mana* rice variety was replaced by CR-1017 or CR1018 after the first year of interventions). The preference analysis indicated that yield was the most dominant factor to choose a rice variety by the farmers followed by resistance to lodging and duration of crop. Early-maturity rice variety was more preferred because it created the possibility of taking additional crop in subsequent seasons.

## Socio-economic impact of cropping system intensification

### Adoption of new/improved cropping systems

As the cropping systems experiments progressed more and more farmers participated and became active participants in the project. The project interventions also included leased-in/share cropper farmers enabling a higher level of community participation which increased the enthusiasm among the farmers and their participation was very active. The activities were initiated during 2016–2017 with 61 collaborative farmers, which increased to 111 farmers in 2017–2018, 188 farmers in 2018–2019, and 338 farmers in 2019–2020. Besides these collaborative farmers, the project activities were also extended to 214 farmers (other) either through input or technical support during 2016–2017 covering 42 ha, increased to 304 farmers (45 ha) in 2017–2018, by 2019–2020, the project activities covered over 700 numbers of farmers/farm women toward increasing the cropping intensity and agricultural livelihoods. The technical/input support was extended to a large number of farmers as per their willingness to adopt the new cropping systems. New crop varieties for potato, rice varieties (short duration or submergence tolerant), maize or rock phosphate as soil ameliorants for acid saline soil were made available to the farmers through the project interventions. Farmers continued to practice the new cropping systems and different socio-economic benefits were accrued (Ray et al., 2019; ICAR-CSSRI CSI4CZ, 2020). Besides, training on improved cropping management practices and varieties was imparted to about 685 farmers (470 male and 215 female) in 25 numbers of events. The endline survey indicated that all collaborative farmers and over 65% of other farmers adopted new/improved cropping systems in the study area.

TABLE 2 Ranking of farmers criteria for preferring rice varieties.

| Preference criteria | Ranks (*kharif* rice) | | | | | RBQ score | Rank |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| Yield | 6 | 6 | 3 | 3 | 1 | 46.67 | 1 |
| Tolerant to salinity | 1 | 0 | 1 | 3 | 3 | 11.33 | 8 |
| Capacity to withstand waterlogging/plant height | 2 | 2 | 2 | 4 | 3 | 23.33 | 4 |
| Pest and disease resistant | 2 | 1 | 2 | 2 | 3 | 18.00 | 5 |
| Quality of straw for thatching/fodder/fuel | 1 | 3 | 2 | 2 | 3 | 20.00 | 6 |
| Resistance to lodging | 4 | 4 | 3 | 2 | 2 | 34.00 | 2 |
| Grain quality for better market price | 1 | 1 | 3 | 2 | 3 | 16.67 | 7 |
| Duration of crop | 3 | 3 | 4 | 2 | 2 | 30.00 | 3 |
| No of observations (N) | 20 | 20 | 20 | 20 | 20 | | |

## Impact of interventions on prevailing cropping practices

Changes in the cultivation practices of farmers were analyzed for both *kharif* and *rabi* seasons. The project was primarily targeted to increase cropping systems intensification during *rabi* season, however, also involved some activities in improving *kharif* season rice, such as the selection of early maturing rice varieties, establishment methods, amelioration of acid saline soils through lime/rock phosphate application along with green manuring and technology on vegetable cultivation in sacks (bags filled with soil) along with *kharif* rice. A comparison of farm-level cropping area before and after the project, indicated that there was no significant change in area under *kharif* crops, but due to the introduction of better varieties, establishment methods, quality seeds, and vegetables in rice fields, higher net return was realized (Table 3). Additionally, an average net return of ₹20,206 was obtained from 1,153 $m^2$ cultivated area due to rice-plus-vegetable cultivation in sacks (bags) as compared to ₹1,195 from conventional rice cultivation alone in the same area. The impact of the project interventions was more visible in *rabi* season cultivation. A significant change in area and production was observed for potato, green gram, lathyrus, and vegetables. All these expansions in areas successfully reduced the extent of *rabi* season fallow area (30–35%) in the study area. Additional crops were taken during *rabi* season with higher cropping intensification, and resulted into higher production and income. Overall, the interventions were successful to increase the cropping intensity to around 202% from 123 to 142%. An increase in cropping system intensification was recorded even higher (300%) for the vegetable-vegetable-vegetable cropping system under a solar-powered drip irrigation system (Mandal et al., 2020). The impact of the project was also analyzed through estimating the change in expenditures and returns from the cultivation practices, before and after the project for both *kharif* and *rabi* season crops. It indicated, with a 19% increase in expenditures, the average gross return from the cultivation ($households^{-1}$) increased by 46%. Out of this total increase, a higher return was obtained from *rabi* season cultivation (88% increase) as compared to *kharif* season cultivation (42%). In both seasons, expenditures and returns were increased but the incremental return was higher in *rabi* season as compared to *kharif* season, and also indicated that interventions in the project were successful.

## Farmers' perception on different interventions for cropping system intensification

During the project period, several interventions were attempted and demonstrated with the active participation of the farmers. Farmers' perception of these interventions was recorded on the basis of (a) percentage of farmers who liked the intervention and were willing to adopt, (b) they liked the interventions but were not sure to adopt due to some specific reasons like suitable land availability or capital inadequacy, and (c) farmers who were undecided whether to adopt the specific interventions (may need more experiments to gain confidence). Also, the reasons for their responses (yes or no) were recorded for each of these interventions. The most preferred interventions reported by the farmers were, ZT potato (Sarangi et al., 2018, 2020), vegetables in sacks with *kharif* rice, straw mulching, green manuring, lime applications, and growing new crops like broccoli, green gram, mustard, sunflower, maize and other vegetables (Table 4). The low-cost drip irrigation method, direct seeded rice, and drum seeded rice method was also preferred by the farmers but they were not quite sure whether to adopt on a large scale, primarily due to erratic rainfall pattern and operating very small area of land. Overall, it was realized that farmers prefer interventions that require less water and resources but give higher production (laborer and fertilizers), conserved moisture, improved soil quality, and provided

TABLE 3 Cultivation practices before and after the project interventions.

| Cultivation practices | Major varieties/crops | Average area (ha households$^{-1}$) | | 't' value | Implications |
|---|---|---|---|---|---|
| | | Before | After | | |
| ***Kharif* season** | | | | | |
| *Kharif* Rice | *CR 1017, CR1018, CR1075,Prateeksha, Swarna* | 0.43 | 0.43 | 0.53319$^{NS}$ | No change except few varieties and additional return from vegetables in rice fields |
| Mixed crop/homestead plot (non-rice) | *Bittergourd, snake gourd, basella, okhra, colocasia, brinjal, cucumber* | 0.05 | 0.07 | 0.47055$^{NS}$ | No area change, increased production by better seeds |
| Vegetables with *kharif* rice | *Bittergourd, snake gourd, cucumber, bottlegourd* | 0.00 | 0.11 | – | Additional cropping intensifications with rice in *kharif* season |
| ***Rabi* season** | | | | | |
| *Rabi* rice | *Lal minikit (WGL 20471), Sada minikit (IET 4786)* | 0.21 | 0.24 | 0.33385$^{NS}$ | 3% additional farmers (from 19 to 22%) grew *rabi* rice as compared to baseline |
| Potato | *Kufri Pukhraj, Kufri Jyoti* | 0.02 | 0.06 | 3.59765*** | Increased area and production significantly |
| Moong/Lathyrus# | *Sonamoong, Chaiti moong* | 0.02 | 0.07 | 2.9014** | Increased area and production significantly, decreased *rabi* fallow |
| Vegetables, mixed vegetables plot (non-rice) | *Brinjal, tomato, chili, cucumber, Cabbage, Cauliflower* | 0.01 | 0.05 | 2.6290** | Number of crops introduced, more options, increase production and return |

NS indicates not significant, ** and *** indicates significant at 10 and 5% level of significance. #Scientific names of moong and lathyrus are Vigna radiata and Lathyrus sativa, respectively. Vegetables with *kharif* rice was first time introduced cropping systems in the study area, hence 't' test was not required.

vegetables throughout the year. Key reasons for not being able to adopt the new interventions despite they liked was a lack of suitable land area and uncertainty of availability of quality inputs.

## New technical knowledge and likely implications on cropping practices

The project activities in the study area helped farmers to acquire new knowledge of cultivation practices and cropping systems. Based on these experiences, farmers also reported adopting some changes in their future cultivation practices. Results of the ZT potato cultivation with rice straw mulching helped to understand that the success of this technology depends on the optimum depth of straw mulching, proper nutrient application, use of water-soluble fertilizers, use of organic manure, and maintaining recommended spacing (Table 5). The low-cost drip irrigation system was good in terms of growing more crop with less water and the number of vegetables it was feasible to grow throughout the year. The solar-powered drip irrigation system can be adopted if the subsidy (80%) is provided by the government. Growing vegetables in sacks along with the rice was easy, and early sowing of crop varieties helped to grow additional crops, which otherwise remained fallow during post-*kharif* season. Following good agricultural practices like green manuring (mainly *Sesbania* sp.), recommended doses of fertilizer, and lime application in acid sulfate soil can reduce the cost of cultivation while providing better production and return. Options for several new crops (maize, capsicum, sunflower, broccoli, onion, garlic) were successfully demonstrated in farmers' fields and they were confident to choose among those alternatives. Besides, all the knowledge was also shared among the farmers through farmers-farmers interaction. They reported that around 47% of the collaborator farmers discussed their knowledge with 11–20 fellow farmers; 32% discussed with 1–10 fellow farmers and 11% of the farmers discussed with 21 and above other farmers. Overall, on average each farmer discussed their activities with around 15 other farmers and many of them were willing to adopt some of the interventions on their own in other areas of the coastal zone.

# Constraints, issues, and possible ways forward toward adoption of new practices

The constraints of the coastal zone were kept in mind while formulating and implementing the cropping system intensification strategies (Bandyopadhyay et al., 2011; Mandal et al., 2011b; Burman et al., 2015). Successful demonstration of the interventions was able to increase the cropping system intensifications through different alternative crop choices, crop establishment methods, and improve soil and water management method. However, several constraints still remained critical for decision-making by the farmers. Some

TABLE 4 Farmers perceptions on interventions and improved practices of agriculture.

| Interventions | % respondents liked and willing to adopt | Reasons | % respondents liked but not sure to adopt | Reasons | Can't say/undecided |
|---|---|---|---|---|---|
| Zero tillage potato | 99.00 | Less water, low cost, less labor | 1.00 | Lack of suitable land | 0.00 |
| Solar powered drip irrigation system | 77.00 | Less water, year round cultivation | 12.00 | Costly, difficult to mange | 11.00 |
| Low cost drip irrigation system | 86.00 | Less water, year round crops, more production | 8.00 | Difficult to manage, maintenance cost | 6.00 |
| Vegetables in sack with rice | 98.00 | Easy method, additional return | 2.00 | Very tiny land available | 0.00 |
| Sunflower | 64.00 | Oil for home consumption | 30.00 | Input not available, bird damage | 6.00 |
| Maize | 58.00 | Multipurpose use—food and feed | 23.00 | Good but can't sell or process | 19.00 |
| Direct seeded rice | 61.00 | Can be sown early, easy method | 22.00 | Weed, heavy rain may damage crop | 17.00 |
| Drum seeded rice | 53.00 | Easy method, less labor, less time to sow | 19.00 | Not sure about uniformity of spacing | 28.00 |
| Plastic mulch | 61.00 | More production, less water, less weed | 31.00 | Not available, additional cost, not good for environment | 8.00 |
| Straw mulch | 94.00 | More production, conserve water, less water, less weed | 6.00 | Straw not available at home, more labor | 0.00 |
| Capsicum | 42.00 | May give good return | 11.00 | Not suitable to grow | 44.00 |
| Broccoli | 69.00 | Profitable, grow well | 11.00 | Seed availability, price uncertainty | 19.00 |
| Mustard | 88.00 | Oil for home consumption, oil cake | 8.00 | Doesn't grow well, chances of crop failure | 3.00 |
| Green gram | 97.00 | Low cost, good production, additional crop, home consumption | 3.00 | Land not available, Low land | 0.00 |
| *Sesbania sp.* as green manure | 100.00 | Good for soil, less fertilizer required, fertility improves | 0.00 | – | 0.00 |
| Lime application | 94.00 | Soil quality improves, more production | 2.00 | Not available locally, costly | 1.00 |
| Other vegetables | 81.00 | Additional income, more option | 19.00 | Suitable land area not available | 0.00 |

of these critical constraints might be mitigated through the knowledge gained from experiences of the action research and some needed policy attention for the out-scaling of such practices in the coastal zone. Key constraints, as perceived by the farmers were, more water in *kharif* (waterlogged situation), less water in *rabi* (good quality), soil salinity, water salinity, input unavailability in time and quality, high input cost, disposal of crops with remunerative price, limited access to technical know-how, risk in agriculture and insufficient capital (Table 6). Uncertainty of input costs, productivity, and profitability are serious concerns for sustaining dry-season crop production (Mainuddin et al., 2021a,b). Prevailing agricultural risks (production, marketing, and environmental) impede farmers' decision-making on the adoption of newer interventions, despite having favorable economics. Agricultural risks and coping strategies both at the farm-level and on the regional scale needed special attention, especially managing the environmental risks (Ali and Kapoor, 2018; Mandal et al., 2018b; Mainuddin et al., 2019, 2020). The cropping system research interventions revealed that alternate crop establishment methods (e.g., direct seeded rice, drum seeding rice), early sowing of crops through choosing early maturing crop varieties (for *kharif* rice), improved irrigation methods (drip irrigation system), moisture conservation through mulching (straw/plastic),

TABLE 5 New technical knowledge acquired and likely change over the existing agricultural practices.

| Technology/ interventions | Knowledge acquired | Likely change to adopt |
|---|---|---|
| Zero Tillage Potato | • Depth of straw mulching to be more<br>• Foliar/liquid application of fertilizer<br>• Organic manure during planting | • Will follow the improved methods of fertilizer applications and mulching depth<br>• Spacing and organic manure application |
| Low cost drip irrigation method | • More crop with less water<br>• Vegetables cultivation year-round<br>• More production from same land | • Suitable for highland area<br>• Management of drip pipes be made easy<br>• Willing to adopt with overhead tank, pump and less number of pipes |
| Solar powered drip irrigation method | • More crop with less water<br>• Vegetables cultivation year-round<br>• More production from same land<br>• Easy irrigation method | • Farmers willing to adopt, if subsidy are provided<br>• Needs to be made low cost/affordable<br>• Straw mulch preferred over plastic mulch |
| Vegetable in sack with *kharif* rice | • New and easy method of growing vegetables in rice<br>• Additional return from same land<br>• Women friendly | • Willingness to adopt by many farmers<br>• Will follow the new methods for growing vegetables in *kharif* and even in post-*kharif* seasn |
| Early sowing rice varieties | • Short duration rice varieties to be preferred<br>• Early harvest (15-20 days) is good for sowing next crop<br>• Utilization of field moisture and opportunities for many *rabi* crops | • Preference will be given for early maturing rice varieties<br>• Higher cropping system intensification with additional crops<br>• *Rabi* fallow land can be reduced by 30-35% |
| Reducing cost of cultivation through better nutrient management | • Following recommended fertilizer dose, adding green manure, moisture conservation through straw mulching and using quality seeds | • Good agricultural practices learned will be followed<br>• More organic manure to be used as far as possible |
| Lime application for managing acid sulfate soil | • Improves fertility of acid sulfate soil<br>• Increases crop yields significantly<br>• Crop losses reduced | • Lime application will be followed, subject to availability of lime in local market |
| New crops (maize, capsicum, sunflower, broccoli, onion, garlic) | • Several new crops were introduced and crop establishments were successful<br>• New cropping options realized<br>• Maize is a potential crop | • Farmers will continue growing selected crops like broccoli, garlic, onion<br>• Maize can be taken up, but need value addition toward like conversation to animal feed |

choosing alternative crops from several options in *rabi* season, establishing institutional linkages (research organization, state government agencies, non-governmental organizations, social networking) for dissemination of technical know-how and input delivery by using information technologies was helpful to mitigate these critical constraints (Mandal et al., 2011a,b; Kabir et al., 2017c; Mishra et al., 2017; Mahanta et al., 2019).

## The participation of women in agricultural operation

The participation of women in agricultural activities was an integral part of all kinds of farming systems. During 2019–2020, project activities were implemented in about 335 farmers including 201 male and 137 female farmers covering about 20 crops to increase cropping intensity through the introduction of improved management practices, new crops, and varieties. Women folk in the farm families performed routine daily work starting from 4.30 am up to sleep at 10 pm. The various activities performed by them are, cleaning house, cleaning cattle shed area, feeding animals, poultry, duck, goat; fetching water, managing homestead garden, kitchen work; helping at field activities, cultivation, and entertainment. Very often role and contribution of women in agriculture remained unnoticed or under-appreciated. Increasing income for women farmers or women engaged in agriculture needed special attention. It was noted that the livestock components within the farming system provided additional income (10–20%) opportunities, particularly to women farmers with a marginal increase (1–2 h daily) in their existing workload (Supplementary Table A5, Annexure II). Cropping system intensification created opportunities to increase overall households' income (2–5 times) and simultaneously also increased workload (2–3 h daily) of women to varying extents. The participation of women in some of the agricultural activities continued throughout the year and some others were seasonal. Active participation in homestead gardening, vegetable harvesting, weeding/intercultural operations were normally practiced by

TABLE 6 Framers perception on constraints and possible mitigation options to take forward the successful interventions.

| Critical constraints | % farmers reported | Likely solution/options | Key knowledge gained from research interventions |
|---|---|---|---|
| **Environmental** | | | |
| More water in *kharif* (waterlogged/prolonged inundation) | 95 | Embankments, drainage, canal renovation and excavation | Crop establish method like direct seeded rice |
| Less water (good quality/non-saline) in *rabi* | 100 | Conserve freshwater, rainwater harvesting, canal renovation and excavation | Early sowing of crops/varieties from many alternative crops demonstrated increased choice. Drip irrigation method |
| Soil salinity | 100 | Efficient water management, mulching, early sowing of crops, salt tolerant crops, use of field water as much as possible | Improved irrigation method using solar powered and low cost drip system can manage soil salinity |
| Water salinity | 90 | Use of pond/canal water, salt tolerant crop/variety adoption | Efficient irrigation method with straw and adoption of plastic mulching |
| **Institutional** | | | |
| Unavailability of quality inputs | 86 | Formation of farmers group like producer's organization | Quality inputs are available and can be delivered the villages. Need support from service providers through institutional linkages |
| Input unavailability in time | 90 | Formation of farmers group like producer's organization | Establishing linkages with formal institutions/organization |
| High input cost | 90 | Bulk purchase through formation of farmers group like producer's organization | Reducing chemical fertilizer use by supplementing green manure, organic manure like FYM, bulk purchase |
| Limited access to technical know-how | 85 | Continuous linkages with local extension officers (ADAs, govt. of West Bengal), non-governmental organizations or Scientists through social media or using information technologies | Establishing linkages with resource persons of formal organization like ICAR-CSSRI, KVKs, State University, ADAs and continuing discussion through using social media platform |
| **Economic** | | | |
| Marketing of produce with remunerative price | 82 | Direct selling to city market through bulk selling as farmers group | Selection of crops having market demand, new crops and early sowing |
| Risk in agriculture (production and marketing) | 95 | Institutional linkages for bulk purchase and direct selling of produce in wholesale markets/consumer. Access to compensation during disasters or participation in crop insurance schemes | Contingency planning like keeping ready seeds/planting material in case of damage/calamities. Early sowing, choosing high value crops and growing multiple crops |
| Insufficient capital | 90 | Access to Govt. scheme (*Krishak Bandhu*), choosing profitable crops based on market demand | Increasing marketable surplus through multiple cropping and saving from additional return |

ADA, assistant director of agriculture; ICAR-CSSRI, ICAR central soil salinity research institute; KVV, krishi vigyan kendra.

the women folk throughout the year and typically they spent 2–3 h daily on these activities. Women also actively participated in seasonal activities like transplanting of rice (almost 30–35% are women laborers), intercultural operations, weeding in rice fields, harvesting of rice and vegetables/maize, and carrying the harvested crops. Seasonal work participation of women varied from 2 to 3 h to full-time laborers (8 h a day). Women folk reported that their participation has increased (40–45%) in agricultural activities particularly after the cyclone *Aila* in 2009 (seawater intruded and a large area remained inundated for several weeks making the land less/unproductive for the subsequent 3 years), due to which large scale male migrated for the search of alternative livelihoods. The women farmers opined that the higher cropping system intensification will increase their work load marginally but they were happy to participate in the activities so long it was profitable. Women folk actively participated in decision-making such as rice variety selection and homestead gardening. However, the decision on fertilizer and pesticide application was taken by male farmers only. Keeping in view the interest of women farmers and to increase their participation in agricultural activities, 3 groups (5 women in each group) were provided small irrigation pumps to be utilized on sharing basis. With the help of pumps, these women farmers could grow additional crops (such as ZT-potato) in the fields and generate additional income, managed by themselves. The creation of more such interest groups among women farmers can be gainful engagement in the region to increase agricultural production and income.

## Factors affecting adoption of new/improved cropping systems

The field trials successfully evolved or improved several cropping systems that could be suitable for smallholder farmers in the coastal zone of West Bengal, India. These new options have the potential to increase the farmers' income substantially. Binary dependent variables were constructed as 1 for farmers whose cropping intensity was higher than the baseline level of intensification (142%) or 0 otherwise. The extent of homestead area managed by individual farm households, income from agriculture, income from off-farm activities, and the number of perennial ponds available for irrigation water, significantly influenced the adoption of higher cropping intensification positively (Table 7). Homestead areas are small production units that are suitable to manage even with limited resources and are managed by the farmers throughout the year. Both incomes from agriculture, as well as off-farm sources, induced the higher adoption of new/evolved cropping systems. Smallholder farmers are constrained with insufficient capital to invest in agriculture and the off-farm income increased their capacity to invest in the new cropping systems in expectation of a better income. The Coastal zone of West Bengal has very limited irrigation water resources and the rainwater stored in ponds/canals is mostly used for cultivation during *rabi* season. Therefore, the number of perennial ponds available for farm households was a very important factor to facilitate the adoption of higher cropping intensification. It was interesting to note that the operational holdings were not influencing (significantly) the adoption of higher cropping intensification. The probable reason is that the availability of a sufficient quantity of good quality irrigation water (non-saline) in the *rabi* season affected the large-scale adoption of new cropping systems, despite having the potential for higher profitability. Other factors that remained non-significant in changing the adoption of new cropping systems were, the number of male or female adults in the family, whether the primary occupation was agriculture or non-agriculture, age of the respondent farmers, education status, and the distance from the nearest markets.

## Conclusion

The cropping systems practiced by smallholder farmers play a vital role in agri-food production systems and help to reduce hunger, improve nutrition, and provide livelihoods to millions across developing countries. The number of smallholder farmers are rapidly increasing in both developing and underdeveloped countries, however, they are increasingly facing challenges to running profitably. Cropping system intensification (CSI) can be one of the ways to make such production systems more remunerative for these farmers. The agricultural cropping options are highly restricted with more water during the wet (*kharif)* season (waterlogged), scarcity of good quality irrigation water, and soil salinity during the dry (*rabi)* season in the Ganges delta. Farmers sacrifice the expected higher return through intensive cropping system attributed to different socio-economic factors, often remaining unnoticed. Therefore, the socio-economic suitability of new crops and management options were evaluated by accounting the benefits of adoption and identifying various constraints in adoption. Baseline and end-line surveys were conducted to quantify the impact of interventions. Behavioral analysis was carried out to identify factors affecting large-scale adoption of the new/improved cropping systems evolved. The socio-economic impact study revealed that the field trials and subsequent adoption of evolved cropping systems successfully increased the cropping intensity in the study area. Cropping system intensification was quite successful and there were several opportunities to achieve higher cropping intensities (from baseline 123–142% to over 202–300%) with substantially higher returns (2–5 times) as compared to the existing practices. The experiments showed there were a number of feasible cropping options that could be promoted (*kharif* rice-ZT potato-green gram, *kharif* rice-ZT potato, *kharif* rice-maize, vegetables-vegetables). Besides, some existing cropping options (*kharif* rice, *kharif* rice-ridge potato, mixed cropping system) were improved through suitable soil and water management as demonstrated at farmers' fields. These interventions increased the smallholder farmers' income substantially by reducing the yield gap in the coastal zone. The cropping system intensification was also found to be encouraging for the women farmers that could empower them financially. Promotion of new cropping systems may be complemented with farm-level risk mitigation measures like quality input supply to the region, regular weather advisory services, and disease or pest attack forecasting, because weather aberrations are more critical factors than climate change as far as sustaining the farm-level production management are concerned. Farmers' perception of cropping system intensification indicated that the project interventions helped them to acquire new knowledge on cultivation practices and adopted better cropping systems. For example, the ZT potato cultivation with rice straw mulching helped them to realize better yields that can be obtained through using optimum depth of straw mulching, proper nutrient application, use of water-soluble fertilizers, use of organic manure, and maintaining recommended spacing. The low-cost drip irrigation system facilitated the growing of more crops with less water and a number of vegetables were feasible to grow throughout the year. Interventions for cropping system intensification interventions

TABLE 7 Factors affecting adoption of higher cropping system intensification.

| Factors | Name | Co-efficient | SE |
|---|---|---|---|
| A | Constant | −4.582** | 2.262 |
| $X_1$ | Operational holding size (average in ha household$^{-1}$, excluding homestead area) | −4.869*** | 1.516 |
| $X_2$ | Homestead area (average in ha household$^{-1}$) | 0.790 | 13.193 |
| $X_3$ | Income from agriculture (in ₹year$^{-1}$ household$^{-1}$) | 0.053*** | 0.020 |
| $X_4$ | Off-farm income (in ₹year$^{-1}$ household$^{-1}$) | 0.086*** | 0.032 |
| $X_5$ | Number of adult male (Number household$^{-1}$) | 0.085 | 0.266 |
| $X_6$ | Number of adult female (Number household$^{-1}$) | −0.556 | 0.446 |
| $X_7$ | Number of perennial ponds (Number of ponds household$^{-1}$ available having water for 9 or more months) | 1.003*** | 0.388 |
| $X_8$ | Primary occupation (If agriculture = 1, 0 otherwise) | 0.498 | 0.652 |
| $X_9$ | Age of respondents (Years in number) | 0.040 | 0.031 |
| $X_{10}$ | Education status (Number of years of schooling) | 0.058 | 0.215 |
| $X_{11}$ | Distance of nearest market fields (in km) | −0.257 | 0.242 |
| | −2 Log likelihood | | 79.592 |
| | Correct prediction (%) | | 75.60 |
| | No of observation | | 90 |

***, **, and * indicated level of significances at 1, 5, and 10% level, respectively.
Authors' estimation based on primary survey baseline (2018–2019) and end line (2020–2021).

were found to be profitable, employment generating, suitable for smallholder farmers, and profitable for the region. The amount of homestead land possessed, income from agriculture, off-farm income, and the number of perennial ponds as irrigation water sources were the most important factors in the adoption of new cropping systems in the coastal zone. However, the size of the operational holding was neutral to the adoption of higher cropping intensification in the study area. The socio-economic impact study identified the interventions that are preferred by the smallholder farmers in the coastal zone and those can be out-scaled in the larger part of the Ganges delta for increased income, better livelihoods, and higher social benefit.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

SM, SKS, and MM contributed equally to research experiment design, data collection, analysis, and manuscript writing. KM, UM, and DB contributed in setting experiments and data collection. SD helped in data collection. PS and BM contributed in manuscript writings. All authors contributed to the article and approved the submitted version.

## Funding

The study was conducted by ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town, West Bengal as part of the project Cropping system intensification in the salt-affected coastal zones of Bangladesh and West Bengal, India (project ID LWR/2014/073) funded by the Australian Center for International Agricultural Research (ACIAR) and Indian Council of Agricultural Research (ICAR). Authors thank profusely all the farmers in the study area who have actively participated in the project. Authors acknowledge with thanks the support extended by ICAR, New Delhi for implementing this project and PME Cell of ICAR-CSSRI, Karnal (Ref. No. Research Article 25/2021) for reviewing and value addition in the paper.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer AP declared a shared affiliation with the authors SM, SKS, KM, UM, DB, SD, PS, and BM to the handling editor at the time of review.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1001367/full#supplementary-material

## References

ACIAR (2020). *Cropping Systems Intensification in the Salt Affected Coastal Zones of Bangladesh and West Bengal, India (CSI4CZ).* Final report, ISBN 978-1-922345-79-0, p. 121. Available online at: https://www.aciar.gov.au/publication/cropping-system-intensification-salt-affected-coastal-zones-bangladesh-and-west-bengal (accessed April 15, 2022).

Alam, E., and Dominey-Howes, D. (2014). A new catalogue of tropical cyclones of the Northern Bay of Bengal and the distribution and effects of selected land falling events in Bangladesh. *Int. J. Climatol.* 35, 801–835. doi: 10.1002/joc.4035

Alam, M. J., Al-Mahmud, A., Islam, M. A., Hossain, M. F., Ali, M. A., Dessoky, E. S., et al. (2021). Crop diversification in rice—based cropping systems improves the system productivity, profitability and sustainability. *Sustainability* 13, 6288. doi: 10.3390/su13116288

Ali, J., and Kapoor, S. (2018). Farmers' perception on risks in fruits and vegetables production: an empirical study of Uttar Pradesh. *Agric. Econ. Res. Rev.* 21, 317–326. doi: 10.22004/ag.econ.47881

Anderson, J. R., and Dillon, J. L. (1992). "Risk analysis in dryland farming systems," in *Farm Systems Management Series No. 2* (Rome: FAO), 117.

Aravindakshan, S., Rossi, F., Amjath-Babu, T. S., Veettil, P. C., and Krupnik, T. J. (2018). Application of a bias-corrected meta-frontier approach and an endogenous switching regression to analyze the technical efficiency of conservation tillage for wheat in South Asia. *J. Prod. Anal.* 49, 153–171. doi: 10.1007/s11123-018-0525-y

Bandyopadhyay, B. K., Burman, D., and Mandal, S. (2011). Improving agricultural productivity in degraded coastal land of India: experiences gained and lessons learned. *J. Indian Soc. Coast. Agric. Res.* 29, 1–9. Available online at: https://www.iscar.org.in/_files/ugd/c3cacb_7d758f73929b409fa1de1f303b228ab8.pdf?index=true

Bell, R. W., Mainuddin, M., Barrett-Lennard, E. G., Sarangi, S. K., Maniruzzaman, M., Brahmachari, K., et al. (2019). Cropping systems intensification in the coastal zone of the Ganges Delta: opportunities and risks. *J. Indian Soc. Coast. Agric. Res.* 37, 153–161.

Berzsenyi, Z., Gyorffy, B., and Lap, D. (2000). Effect of crop rotation and fertilisation on maize and wheat yields and yield stability in a long-term experiment. *Eur. J. Agron.* 13, 225–244. doi: 10.1016/S1161-0301(00)00076-9

Bhattacharya, J., Mondal, M. K., Humphreys, E., Saha, N. K., Rashid, M. H., Paul, P. C., et al. (2015). "Rice-rice-rabi cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh," in *Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices. Conference Proceedings, CGIAR Challenge Program on Water and Food (CPWF)*, Sri Lanka (Colombo), eds E. Humphreys, T. P. Tuong, M. C. Buisson, I. Pukinskis, and M. Phillips, 436–448.

Burman, D., Maji, B., Singh, S., Mandal, S., Sarangi, S. K., Bandyopadhyay, B. K., et al. (2018). Participatory evaluation guides the development and selection of farmers' preferred rice varieties for salt- and flood-affected coastal deltas of South and Southeast Asia. *Field Crops Res.* 220, 67–77. doi: 10.1016/j.fcr.2017.03.009

Burman, D., Mandal, S., Bandyopadhyay, B. K., Maji, B., Sharma, D. K., Mahanta, K. K., et al. (2015). Unlocking production potential of degraded coastal land through innovative land management practices: a synthesis. *J. Soil Salinity Water Qual.* 7, 12–18. Available online at: http://issswq.in/download/2015-volume-7-issue-1-june/

Carcedo, A. J. P., Bastos, L. M., Yadav, S., Mondal, M. K., Jagadish, S. V. K., Kamal, F. A., et al. (2022). Assessing impact of salinity and climate scenarios on dry season field crops in the coastal region of Bangladesh. *Agricul. Syst.* 200, 103428. doi: 10.1016/j.agsy.2022.103428

Census of India (2011). *District Census Handbook: South 24 Parganas, Village and Town Wise Primary Census Abstract, Series 20, Part XII-B, Directorate of Census Operation, Govt. of West Bengal.* New Delhi: Census of India. Available online at: www.censusindia.gov.in (accessed May 20, 2020).

Childs, N., and Kiawu, J. (2009). *Factors Behind the Rise in Global Rice Prices in 2008. A Report from the Economic Research Service.* Washington, DC: United States Department of Agriculture. Available online at: https://www.ers.usda.gov/webdocs/publications/38489/13518_rcs09d01_1_.pdf?v=41056 (accessed February 10, 2021).

Dillon, J. L., and Hardaker, B. (1993). *Farm Management Research for Small Farmer Development, Vol. 6.* Rome: Food and Agriculture Organization of the United Nations (FAO).

Dolinska, A. (2017). Bringing farmers into the game. Strengthening farmers' role in the innovation process through a simulation game, a case from Tunisia. *Agric. Syst.* 157, 129–139. doi: 10.1016/j.agsy.2017.07.002

FAO. (1998). "Issues, perspectives, policy and planning processes for integrated coastal area management," in *Integrated Coastal Area Management and Agriculture, Forestry and Fisheries. FAO Guidelines, Environment and Natural Resources Service*, ed. N. Scialabba (Rome: FAO), 256. Available online at: https://www.fao.org/3/W8440e/W8440e02.htm#TopOfPage (accessed May 21, 2021).

Fisher, R. A. (2015). Definitions and determination of crop yield, yield gaps, and of rates of change. *Field Crops Res.* 182: 9–18. doi: 10.1016/j.fcr.2014.12.006

Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., et al. (2013). Sustainable intensification in agriculture: premises and policies. *Science* 341, 33–34. doi: 10.1126/science.1234485

Ghosh, S., and Mistri, B. (2020). Drainage induced waterlogging problem and its impact on farming systems: a study in Gosaba island, Sundarban, India. *Spatial Inform. Res.* 28, 709–721. doi: 10.1007/s41324-020-00328-8

Goswami, R., Roy, K., Dutta, S., Sarkar, S., Brahamachari, K., Nanda, M. K., et al. (2021). Multifaceted impact and outcome of COVID-19 on small holder agricultural systems: integrating qualitative research and fuzzy cognitive mapping to explore resilient strategies. *Agricul. Syst.* 189, 103051. doi: 10.1016/j.agsy.2021.103051

Govt. of India (2020). *Agricultural Statistics at a Glance (2019).* New Delhi: Govt. of India. Available online at: https://eands.dacnet.nic.in/PDF/At%20a%20Glance%202019%20Eng.pdf (accessed May 5, 2021).

Govt. of West Bengal (2009). *District Human Development Report: South 24 Parganas, Chapter 9, Sundarbans and Remote Islanders.* West Bengal: Govt. of West Bengal. Available online at: http://www.wbplan.gov.in (accessed April 5, 2018).

Hasan, M. K., and Kumar, L. (2020). Perceived farm-level climatic impacts on coastal agricultural productivity in Bangladesh. *Clim. Change* 161:617–636. doi: 10.1007/s10584-020-02708-3

Humphreys, E., Tuong, T. P., Buisson, M. C., Pukinskis, I., and Phillips, M. (2015). "Revitalizing the ganges coastal zone: turning science into policy and practices," in *Conference Proceedings, Colombo, Sri Lanka, CGIAR Challenge Program on Water and Food (CPWF)*, Sri Lanka (Colombo), 652.

ICAR-CSSRI CSI4CZ (2020). "Final report of ACIAR, Australia funded project on: cropping systems intensification in the salt affected coastal zones of Bangladesh and West Bengal, India (CSI4CZ)," in *Indian Council of Agricultural Research (ICAR)-Central Soil Salinity Research Institute, Regional Research Station, (CSSRI, RRS)*, ed S. K. Sarangi (Canning Town: ICAR-CSSRI CSI4CZ), 94.

Kabir, J. M., Rob, C., Donald, S. G., and Roth, C. H. (2017a). Bio-economic evaluation of cropping systems for saline coastal Bangladesh: II. Economic viability in historic and future environments. *Agric. Syst.* 155, 103–115. doi: 10.1016/j.agsy.2017.05.002

Kabir, J. M., Rob, C., Donald, S. G., and Roth, C. H. (2018). Bio-economic evaluation of cropping systems for saline coastal Bangladesh: III. Benefits of adaptations in current and future environments. *Agric. Syst.* 161, 28–41. doi: 10.1016/j.agsy.2017.12.006

Kabir, M. J., Alauddin, M., and Crimp, S. (2017b). Farm-level adaptation to climate change in Western Bangladesh: an analysis of adaptation dynamics, profitability and risks. *Land Use Policy* 64, 212–224. doi: 10.1016/j.landusepol.2017.02.026

Kabir, M. J., Cramb, R., Gaydon, D. S., and Roth, C. H. (2017c). Bio-economic evaluation of systems for saline coastal Bangladesh: II. Economic viability in historical and future environments. *Agric. Syst.* 155, 103–115.

Krupnik, T. J., Schulthess, U., Ahmed, Z. U., and McDonald, A. J. (2017). Sustainable crop intensification through surface water irrigation in Bangladesh? A geospatial assessment of landscape-scale production potential. *Land Use Policy.* 60, 206–222. doi: 10.1016/j.landusepol.2016.10.001

Kumar, P., and Sharma, P. K. (2020). Soil salinity and food security in India. *Front. Sustain Food Syst.* 4, 533781. doi: 10.3389/fsufs.2020.533781

Kummu, M., Moel, H. D., Salvucci, G., Viviroli, D., Ward, P. J., and Varis, O. (2016). Over the hills and further away from coast: global geospatial patterns of human and environment over the 20th−21st centuries. *Environ. Res. Lett.* 11, 1. doi: 10.1088/1748-9326/11/3/034010

Lin, X., Zhu, D., and Lin, X. (2011). Effects of water management and organic fertilization with SRI crop practices on hybrid rice performance and rhizosphere dynamics. *Paddy Water Environ.* 9, 33–39. doi: 10.1007/s10333-010-0238-y

Mahanta, K. K., Burman, D., Sarangi, S. K., Mandal, U. K., Maji, B., Mandal, S., et al. (2019). Drip irrigation for reducing soil salinity and increased cropping intensity: case studies in Indian Sundarbans. *J. Indian Soc. Coast. Agric. Res.* 37, 64–71.

Mainuddin, M., Alam, M. M., Maniruzzaman, M., Kabir, M. J., Mojid, M. A., Hasan, M. M., et al. (2021a). Yield, profitability, and prospects of irrigated Boro rice cultivation in the North-West region of Bangladesh. *PLoS ONE* 16, e0250897. doi: 10.1371/journal.pone.0250897

Mainuddin, M., Bell, R. W., Gaydon, D. S., Kirby, J. M., Barrett-Lennard, E. G., Razzaque Akanda, M. A., et al. (2019). An overview of the Ganges coastal zone: climate, hydrology, land use, and vulnerability. *J. Indian Soc. Coast. Agric. Res.* 37, 1–11.

Mainuddin, M., Karim, F., Gaydon, D. S., and Kirby, J. M. (2021b). Impact of climate change and management strategies on water and salt balance of the polders and islands in the Ganges delta. *Sci. Rep.* 11, 7041. doi: 10.1038/s41598-021-86206-1

Mainuddin, M., and Kirby, J. M. (2021). Impact of flood inundation and water management on water and salt balance of the polders and islands in the Ganges delta. *Ocean Coast. Manag.* 210, 105740. doi: 10.1016/j.ocecoaman.2021.105740

Mainuddin, M., Maniruzzaman, M., Gaydon, D. S., Sarkar, S., Rahman, M. A., Sarangi, S. K., et al. (2020). Water and salt balance model for the polders and islands in the Ganges delta. *J. Hydrol.* 587, 125008. doi: 10.1016/j.jhydrol.2020.125008

Mandal, S., Bandyopadhyay, B. K., Burman, D., Sarangi, S. K., and Mahanta, K. K. (2011a). *Baseline Report of the NAIP Project on Strategies for Sustainable Management of Degraded Coastal Land and Water for Enhancing Livelihood Security of Farming Communities*. Canning Town: Central Soil Salinity Research Institute, Regional Research Station, 74.

Mandal, S., Burman, D., Bandyopadhyay, B. K., Mandal, U. K., Sarangi, S. K., Mahanta, K. K., et al. (2015a). Crop-fish integration through land shaping models for enhancing farm income under eastern coastal region of India. *Agric. Econ. Res. Rev*. 28, 47–54. doi: 10.5958/0974-0279.2015.00021.X

Mandal, S., Burman, D., Mandal, U. K., Lama, T. D., Maji, B., and Sharma, P. C. (2017). Challenges, options and strategies for doubling farmers' income in West Bengal: reflections from coastal region. Agric. Econ. Res. *Rev*. 30, 89–100. doi: 10.5958/0974-0279.2017.00024.6

Mandal, S., Burman, D., Sarangi, S. K., Bandyopadhyay, B. K., and Maji, B. (2015b). *"Homestead production systems in Sundarbans region of West Bengal, India: current status and opportunities," in Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Conference Proceedings, CGIAR Challenge Program on Water and Food (CPWF)*, Sri Lanka (Colombo), eds E. Humphreys, T. P. Tuong, M. C. Buisson, et al., 241–250.

Mandal, S., Maji, B., Sarangi, S. K., Mahanta, K. K., Mandal, U. K., Burman, D., et al. (2020). Economics of cropping system intensification for small-holder farmers in coastal salt-affected areas in West Bengal: opt ions, challenges and determinants. *Decision* 47, 19–33. doi: 10.1007/s40622-020-00236-8

Mandal, S., Mandal, U. K., Lama, T. D., Burman, D., and Sharma, P. C. (2019b). Economic analysis of farm-level agricultural risks in coastal region of West Bengal in India. *Indian J. Soil Salinity Water Qual.* 11, 269–279. Available online at: http://issswq.in/download/jsswqvol7issue12015/

Mandal, S., Raju, R., Kumar, A., Kumar, P., and Sharma, P. C. (2018a). Current status of research, technology response and policy needs of salt-affected soils in India: a review. *J. Indian Soc. Coast. Agric. Res.* 36, 40–53. Available online at: https://epubs.icar.org.in/index.php/JISCAR/article/view/89004

Mandal, S., Sah, K. D., Das, K., Sahoo, A. K., Reza, S. K., Nayak, D. C., et al. (2018b). Increasing small-holder farmers' income through alternate land-use options in coastal salt-affected areas of West Bengal. *J. Soil Salinity Water Qual.* 10, 268–278. Available online at: http://issswq.in/download/jsswqvol6issue22014/

Mandal, S., Sarangi, S. K., Burman, D., Bandyopadhyay, B. K., Maji, B., Mandal, U. K., et al. (2013). Land shaping models for enhancing agricultural productivity in salt affected coastal areas of West Bengal -An economic analysis. *Indian J. Agri. Econom.* 68, 389–401. doi: 10.22004/ag.econ.206342

Mandal, S., Sarangi, S. K., Burman, D., Bandyopadhyay, B. K., Maji, B., Singh, S. B., et al. (2011b). Agricultural marketing efficiency of major vegetables crops in coastal districts of west Bengal: current status and way forward. *J. Indian Soc. Coast. Agric. Res*. 29, 93–98. Available online at: https://www.iscar.org.in/_files/ugd/c3cacb_7d758f73929b409fa1de1f303b228ab8.pdf?index=true

Mandal, S., Sarangi,. S. K., Burman, D., Mandal, U. K., Maji, B., and Sharma, D. K. (2016). Impact of improved salt tolerant rice varieties on farmers' economy under coastal salt affected areas of Sundarbans. *Paper presented during 11 National Symposium on Innovations in Coastal Agriculture: Current Status under Changing Environment, Indian Society of Coastal Agricultural Research, 14-17 January, 2016, held at ICAR-Indian Institute of Water Management*, (Bhubaneswar: Indian Society of Coastal Agricultural Research).

Mandal, U. K., Nayak, D. B., Mullick, S., Samui, A., Kumar, A., Mahanta, K. K., et al. (2019a). Trend analysis of weather parameters over Indian Sundarbans. *J. Agrometeorol.* 21, 307–315. doi: 10.54386/jam.v21i3.253

Mekoya, A., Oosting, S. J., Fernandez-Rivera, S., and Van der Zijpp, A. J. (2008). Multipurpose fodder trees in the Ethiopian highlands: farmers' preference and relationship of indigenous knowledge of feed value with laboratory indicators. *Agric. Syst.* 96, 184–194. doi: 10.1016/j.agsy.2007.08.001

Mishra, S., Goswami, R., Mondal, T., and Jana, R. (2017). Social networks in the context of community response to disaster: study of a cyclone affected community in Coastal west Bengal, India. *Int. J. Disaster Risk Reduct*. 22, 281–296. doi: 10.1016/j.ijdrr.2017.02.017

Neumann, K., Verburg, P. H., and Stehfest E, Muller, C. (2010). The yield gap of global grain production: a spatial analysis. *Agric. Syst.* 103, 316–326. doi: 10.1016/j.agsy.2010.02.004

Norman, D. W., Newman, M. D., and Ouedraogo. (1981). *Farm and Village Production Systems in the Semi-Arid Tropics of West Africa: An Interpretive Review of Research*. Patancheru: International Crops Research Institute for the Semi-Arid Tropics. p. 94.

Paul, B. K. (2009). Why relatively fewer people died? The case of Bangladesh's cyclone Sidr. *Nat Hazards* 50, 289–304. doi: 10.1007/s11069-008-9340-5

Paul, B. K., and Rashid, H. (2017). *Climatic Hazards in Coastal Bangladesh: Non-Structural and Structural Solutions*. New York, NY: Elsevier. doi: 10.1016/B978-0-12-805276-1.00008-9

Pingali, P., Bigot, Y., and Binswanger, H. P. (1987). *Agricultural Mechanization and the Evolution of Farming Systems in Sub-Saharan Africa*. Baltimore: John Hopkins University Press, 216.

Ray, K., Brahmachari, M., Goswami, R., Sarkar, S., Brahmachari, K., Ghosh, A., et al. (2019). Adoption of improved technologies for cropping intensification in the coastal zone of West Bengal, India: a village level study for impact assessment. *J. Indian Soc. Coast. Agric. Res.* 37, 144–152. Available online at: https://www.jstor.org/stable/4299200

Ray, K., Hasan, S. S., and Goswami, R. (2018). Techno-economic and environmental assessment of different rice-based cropping systems in an inceptisol of West Bengal, India. *J. Clean. Prod.* 205, 350–363. doi: 10.1016/j.jclepro.2018.09.037

Ray, K., Sen, P., Goswami, R., Sarkar, S., Brahmachari, K., and Ghosh, A. (2020). Profitability, energetics and GHGs emission estimation from rice-based cropping systems in the coastal saline zone of West Bengal, India. *PLoS ONE* 5, e0233303. doi: 10.1371/journal.pone.0233303

Remesan, R., Arjun, P., Sangma, M. N., Janardhanan, S., Mainuddin, M., Sarangi, S. K., et al. (2021). Modelling and management option analysis for salty/saline groundwater drainage in a Deltaic Island. *Sustainability* 13, 6784. doi: 10.3390/su13126784

Ritu, S. P., Mondal, M. K., Tuong, T. P., Talukdar, S. U., and Humphreys, E. (2015). "An aus-aman system for increasing productivity of a moderately saline region of the coastal zone of Bangladesh," in *Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices. Conference Proceedings, CGIAR Challenge Program on Water and Food (CPWF), Colombo, Sri Lanka*, eds E. Humphreys, T. P. Tuong, M. C. Buisson, I. Pukinskis, and M. Phillips, 361–388.

SAC (Space Applications Centre) (1992). *Coastal Environment, SAC Report No RSAM/SAC/COM/SN/11/92. DEPARTMENT of Space GOI*. Satellite: SAC (Space Applications Centre), 114.

Saha, N. K., Mondal, M. K., Humphreys, E., Bhattacharya, J., Rashid, M. H., Paul, P. C., et al. (2015). "Triple rice in a year: is it a feasible option for the low salinity areas of the coastal zone of Bangladesh?," in *Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices. Conference Proceedings, CGIAR Challenge Program on Water and Food (CPWF), Colombo, Sri Lanka*, eds E. Humphreys, T. P. Tuong, M. C. Buisson, I. Pukinskis, and M. Phillips, 421–435.

Sarangi, S. K., Maji, B., Digar, S., Mahanta, K. K., Sharma, P. C., and Mainuddin, M. (2018). Zero tillage potato cultivation: an innovative technology for coastal saline soils. *Indian Farm*. 04, 23–26.

Sarangi, S. K., Maji, B., Sharma, P. C., Digar, S., Mahanta, K. K., Burman, D., et al. (2020). Potato (*Solanum tuberosum* L.) cultivation by zero tillage and paddy straw mulching in the saline soils of the Ganges Delta. *Potato Res*. 64, 277–305. doi: 10.1007/s11540-020-09478-6

Sharma, D. K., Singh, A., and Sharma, P. C. (2016). "Role of ICAR-CSSRI in sustainable management of salt-affected soils: achievements, current trends and future perspectives," in *Proceedings of 4th International Agronomy Congress (November 22–26)* (New Delhi: Indian Society of Agronomy), 91–103. doi: 10.13140/RG.2.2.34451.78888

Small, C., and Nicholls, R. J. (2003). A global analysis of human settlement in coastal zones. *J. Coast. Res*. 19, 584–599.

Soltanmohammadi, H., Osanloo, M., and Bazzazi, A. A. (2010). An analytical approach with a reliable logic and a ranking policy for post-mining land-use determination. *Land Use Policy* 27, 364–372. doi: 10.1016/j.landusepol.2009.05.001

Tur-Cardona, J., Bonnichsen, O., Speelman, S., Verspecht, A., Carpentier, L., Debruyne, L., et al. (2018). Farmers' reasons to accept bio-based fertilizers: a choice experiment in seven different European countries. *J. Clean. Prod*. 197, 406–416. doi: 10.1016/j.jclepro.2018.06.172

Urruty, N., Tailliez-Lefebvre, D., and Huyghe, C. (2016). Stability, robustness, vulnerability and resilience of agricultural systems. A review. *Agron. Sustain. Dev*. 36, 15. doi: 10.1007/s13593-015-0347-5

Walker, T. S., and Ryan, J. G. (1990). *Village and Household Economies in India's Semi-arid Tropics*. Baltimore: John Hopkins University Press, 394

Yadav, S., Mondal, M. K., Shew, A., Jagadish, S. V. K., Khan, Z. H., Sutradhar, A., et al. (2020). Community water management to intensify agricultural productivity in the polders of the coastal zone of Bangladesh. *Paddy Water Environ*. 18, 331–343. doi: 10.1007/s10333-019-00785-4

Yu, W. H., Alam, M., Hassan, A., Khan, A. S., Ruane, A. C., Rosenzweig, C., et al. (2010). *Climate Change Risks and Food Security in Bangladesh*. Washington, DC: Earthscan. doi: 10.4324/9781849776387

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 04 January 2023
DOI 10.3389/fsufs.2022.1022213

# Assessing complementary synergies for integrated crop–livestock systems under conservation agriculture in Tunisian dryland farming systems

Boubaker Dhehibi[1]*†, Ayoub Fouzai[2]†, Aymen Frija[1]†, Mohamed Abdel Adhim[2]‡, Hatem Cheikh M'hamed[3]‡, Hassen Ouerghemmi[1]‡ and Mourad Rekik[4]‡

[1]Social, Economic, and Policy Research Team (SEPRT), International Center for Agricultural Research in the Dry Areas (ICARDA), Ariana, Tunisia, [2]Higher School of Agriculture of Mograne, Zaghouan - LR-03AGR02, University of Cartage, Tunis, Tunisia, [3]Laboratory of Agronomy (LA), National Research Agronomic Institute (INRAT), Ariana, Tunisia, [4]Resilient Agro-silvopastoral Systems Program (RASP), International Center for Agricultural Research in the Dry Areas (ICARDA), Ariana, Tunisia

The aim of this paper is twofold. The first objective is to measure the technical efficiency of mixed crop-livestock (CL) smallholder producers operating under conservation agriculture systems in Tunisian rainfed areas. The second objective is to explore complementarities, synergies, and economies of diversification across the different production system components of these crop-livestock producers using the cross-partial derivative framework of output variables in the distance function. A simple random sampling process was employed to select and survey 59 CL smallholders operating under conservation agriculture. The collected data were analyzed using a stochastic input distance function in which synergies were estimated based on the second cross-partial derivative concept of output variables in the distance function. Results show that technical inefficiencies are significant in integrated crop-livestock systems, and there is evidence that economic diversification provides a productivity buffer against climate change threats. As a sustainable intensification strategy, this integrated system also offers a potential advantage. The results further contribute to the debate on crop diversification vs. specialization. Although an enhanced system integration could be a financially and ecologically viable option for mixed crop-livestock systems, more pathways for profitable and viable diversification of cereal-based or orchard-based systems remain to be explored.

KEYWORDS

**conservation agriculture, economies of diversification, input distance function, integrated crop-livestock farming, technical efficiency**

OPEN ACCESS

EDITED BY
Subhasis Mandal,
Central Soil Salinity Research Institute
(ICAR), India

REVIEWED BY
Suresh Kumar,
Central Soil Salinity Research Institute
(ICAR), India
Dwaipayan Bardhan,
Indian Veterinary Research Institute
(IVRI), India

*CORRESPONDENCE
Boubaker Dhehibi
b.dhehibi@cgiar.org

†These authors have contributed equally to this work and share first authorship
‡These authors have contributed equally to this work and share last authorship

SPECIALTY SECTION
This article was submitted to
Land, Livelihoods and Food Security,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 18 August 2022
ACCEPTED 11 November 2022
PUBLISHED 04 January 2023

CITATION
Dhehibi B, Fouzai A, Frija A, Adhim MA, M'hamed HC, Ouerghemmi H and Rekik M (2023) Assessing complementary synergies for integrated crop–livestock systems under conservation agriculture in Tunisian dryland farming systems. *Front. Sustain. Food Syst.* 6:1022213. doi: 10.3389/fsufs.2022.1022213

## Introduction

Intensive farming with limited soil amendments and conservation practices leads to soil erosion and nutrient depletion (IFAD, 2010). Specialization of agricultural systems and the search for economies of scale have guided the evolution of agriculture, with new farming "models" emerging to respond to a growing demand for food. At the same time, it has been suggested that system diversification and integration across production system components would increase household income, reduce vulnerability to shocks, create job opportunities, enhance land productivity, and improve water use efficiency (Moraine et al., 2014). The new paradigm of "sustainable production intensification," as detailed by (FAO, 2010), recognizes *"the need for a productive and remunerative agriculture which at the same time conserves and enhances natural resources and positively contributes to harnessing the environmental services"* (Kassam A. et al., 2009). **[sic]**

Originally, the adoption of conservation agriculture (CA) was mainly driven by severe problems faced by farmers, especially water and wind erosion or drought. Government support has played a significant role in accelerating CA adoption in many countries, leading to relatively increased adoption rates, for example in Kazakhstan and China but also in African countries (Friedrich et al., 2012). The main advantages driving CA adoption can be summarized as follows: (i) better farm economy; (ii) flexible technical possibilities; (iii) yield increase and greater yield stability; (iv) soil protection against water and wind erosion; (v) improved soil health; (vi) better efficiency of nutrients; and (vii) better water economy in dryland areas (Kassam A. H. et al., 2009). Because of these advantages, CA has been widely supported by international donors and development organizations.

Conservation Agriculture (CA) based on direct seeding was initiated in Tunisia between the years 1970 and 1980 through the acquisition of no-till seed drills from the United States (Cheikh M'hamed et al., 2018). In 1999, an integrated agricultural and rural development project (*Projet de Développement Rurale Agricole Intégré,* PDRAI) was implemented in the Siliana region and was partly focused on some agricultural practices under CA (Baccouri, 2008). From 2001 to 2011, the French Facility for Global Environment (FFEM) funded an R&D project, the *Projet d'appui au développement de l'agriculture de conservation* (PADAC project), supported by a range of universities, institutions in the public and private sector and international organizations (INRAT, CTC, ESAK, CIRAD, Cotugrain, and more), and intended to contribute to key development challenges (i.e., food security, environmental sustainability, economic development) through the scaling of CA systems (Raunet et al., 2004). The project was aimed primarily at large-scale farmers (exceeding 100 ha) in the north of the country. Since 2006, interest has focused on small farms (<15 ha), with a project on CA for smallholders funded by the Arab Authority for Agricultural Investment and Development (AAAID) and implemented by CTC and ESAK. From 2012 to 2016, the CANA project "Rapid adoption of Conservation Agriculture in North Africa for Smallholders" was carried out in the Fernana region, funded by ACIAR, managed by ICARDA, and implemented by the INRAT and the INGC. In the framework of this project, a new local prototype of NT seed drills (low-cost no-till drills for smallholders) was designed and manufactured.

The selection of smallholder farms (i.e., 0–15 ha) for this study in this farming system was based on the following: the first criterion was the biophysical context and technical characteristics of this cereal-based rainfed agriculture system under semiarid and with low soil fertility. The size of 0–15 ha was considered to be critical for classifying a farm as small. In other words, it was mainly the low output level of being in an arid rainfed farming system that led us to adopt this classification. Indeed, a maximum of 15 ha of cropping area represents the level under which the resilience of this production system is weak, as well as its economic viability (secure livelihood for the farmers' household). The second criterion was based on national literature findings regarding the farms' categorization in Tunisia. According to Bachta (2011), the number of Tunisian farmers who produce cereals amounts to 38,400. The majority of small farmers works on an area of fewer than 20 hectares. In a second study undertaken by the Tunisian Ministry of Agriculture (cited in Khaldi and Saaidia, 2017) considering 47,700 sampling farms, the number of cereal farmers was estimated at 248,458. About 63% of them (157,000) were considered smallholders, working on areas of 10 hectares or less (MARH, 2006). For the last criterion, we considered the project frame given that, for many concerns on spreading CA technologies, we selected this range (i.e., 0–15 ha) as small-size farms to enhance the adoption of these packages, and the project was included in this challenging (climate change, low soil quality, reduction of rainfall, drought, etc.) farming system.

To resolve the conflict between permanent soil cover with residues and stubble grazing, which is considered the major obstacle to CA adoption in the country, the CLCA project (Integrated Crop-Livestock under Conservation Agriculture for Sustainable Intensification of Cereal-based Systems in North Africa and Central Asia), funded by the International Fund for Agricultural Development (IFAD) and managed by ICRADA, was implemented by INRAT and INGC (2013–2016). As the main result of the project, a stubble grazing model of 30:30 was developed (Guesmi et al., 2019) based on the stocking rate of 30 animals ha$^{-1}$, during a 30-day stubble grazing period. In 2018, the second phase of the CLCA project, "Use of Conservation Agriculture in Crop Livestock Systems (CLCA) in the Drylands for Enhanced Water Efficiency, Soil Fertility and Productivity in

NEN and LAC Countries" was launched and aimed to up-scale CLCA technologies in the semiarid regions of the northern part of the country (Rekik et al., 2021).

Recently, three research projects on CA were funded by the EU through the consortium Partnership for Research and Innovation in the Mediterranean Area (PRIMA) program for 4 years (2020–2023), with Tunisia as a partner in all three projects. These projects implemented in Tunisia by INRAT are: (i) the ConServeTerra project "Overcoming the physical and mental barriers for up-scaling Conservation Agriculture in the Mediterranean" (ii) the 4CE-MED project "Camelina: A Cash Cover Crop Enhancing water and soil conservation in Mediterranean dry-farming systems," and (iii) the CAMA project "Research-based participatory approaches for adopting Conservation Agriculture in the Mediterranean Area".

The CA area in Tunisia increased rapidly during the first years of adoption. Indeed, the CA area was only 27 ha and 55 ha in 1999 and 2000, respectively. The CA area reached 2,893 ha in 2005, 6,000 ha in 2007, 8,000 ha in 2008, and then 12,000 ha in 2010 (Richard, 2005; Angar, 2010). However, in 2016, the areas recorded a significant decrease (Bahri et al., 2018). This decrease was mainly explained by the unavailability of low-cost direct seed drills and the lack of comprehensive CA adoption studies. The CA area in Tunisia stands at around 14,000 ha and is operated by more than 200 farmers using around 107 NT seed drills (Cheikh M'hamed et al., 2018).

Most of the areas under CA in Tunisia are found in semiarid regions, marked by hot summers, cold winters, and low annual rainfall. The average annual rainfall in these regions is between 200 and 450 millimeters per year. The rainfall in these regions is also characterized by a high degree of inter annual variability and intra annual variability during growing season (Cheikh M'hamed et al., 2022). Indeed, a very limited number of rainy days (fewer than 120 days per year in general) and frequent droughts during the growing season combined with high temperatures are common constraints to plant growth, especially for cereal crops, which are strategic crops for the country.

In addition to water scarcity, soil degradation is the main challenge faced by agriculture production systems in semiarid regions of Tunisia. Indeed, it is reported that >3 million hectares (60 % of total cropland in Tunisia) are being eroded or are at a high-water erosion risk (DGACTA., 2017). The effects of water erosion are expected to be exacerbated by CC. Autumn rains contribute to erosion due to the summer overgrazing of crop residues and the absence of vegetation covering the soil. Furthermore, arable soil in Tunisia is increasingly degraded due to inadequately promoted agricultural practices, especially the dominance of conventional production systems based on intensive tillage. These practices have led to land degradation and the depletion of soil fertility and soil water-storage capability (Cheikh M'hamed et al., 2022).

Production systems in these regions are primarily based on field crops, particularly cereals (wheat, barley, and oats) combined with ruminant livestock. In addition, in these regions, CA farmers usually practice cereals crops integrated with livestock activities. Livestock is the backbone of these mixed farming systems because it serves as a means of reducing the risks associated with crop failure, contributes to food security, and considered as an income diversification strategy for resource-poor small-scale farmers (Cheikh M'hamed et al., 2022; Mrabet et al., 2022). Also, livestock is considered by smallholder farmers as a primary asset that can be easily converted into cash during dry years. This is characteristically interconnected with cropping systems through weedy fallows, residue, stubble grazing, and the use of woodlands and rangelands. Because stubble grazing is usually practiced by farmers, they face major challenges in terms of permanent land cover. Indeed, stubble grazing by livestock, especially during the summer, is a traditional and common practice in the region. As a result, under the CA system, maintaining crop residue on field creates a conflict of interest between mulching the soil surface and stubble grazing, especially during the summer (Tittonell et al., 2015). Thereby, trade-offs between the use of stubbles for livestock feeding or to cover the soil must be resolved, particularly in drylands where fodder potential is low. For better crop-livestock integration under CA, it is necessary to combine diversified crop rotation with controlled and improved managed grazing. This can be effective for preserving or even enhancing soil function and health (Mrabet et al., 2022).

In semiarid regions, low rainfall limits crop production. Adoption of CA based on its principles can be effective in mitigating yield loss in dry environments (Cheikh M'hamed et al., 2014; Mrabet et al., 2022). Results from research in Tunisia showed that CA can increase yields after a few years of adoption and make crops more resilient to changing climatic conditions (Cheikh M'hamed et al., 2016; Bahri et al., 2019). CA can reduce drought effects through better water storage and availability during the crop-growing season in wheat-based systems (Mrabet et al., 2022). Indeed, CA allows for improving soil infiltration, thus reducing surface runoff and soil erosion, as well as allowing for a greater soil moisture-holding capacity. This is due mainly to the presence of stubble on the soil surface as mulch, which can increase water infiltration and slow moisture losses through evaporation. Furthermore, the adoption of CA gives more flexibility to farmers for the implementation of field crop management that allows timely planting and input application, despite unfavorable field conditions that prevent such operations in conventional agriculture (Mrabet et al., 2022).

The concept of agricultural diversification is key for the implementation of CA. It states the shift from the dominance of monocrops to the production of diversified crops with varied species (including legumes, forages, and cereals) on a farm or in a region (Petit and Barghouti, 1992). Joshi et al. (2004) defined agricultural diversification as connoting crop mix, enterprise mix, and activity mix at a household level aimed at increasing household profit and wealth.

According to Ryan and Spencer (2001) and Joshi et al. (2006, 2007), the determinants of system diversification can largely be classified into two categories: demand and supply. On the demand side, this classification specifically takes into consideration three criteria: per capita income, population growth, and urbanization. These factors are different from those on the supply side, and some of them are farm-level and include household-level factors, biophysical factors, and risk factors. Others are linked to infrastructure or institutions, technology, and resource endowment factors. Household diversification, on the other hand, could be influenced primarily by key socio-economic factors such as age, gender, education, household dependency ratio, crop and livestock capital, and off-farm income resource activities (Asante et al., 2020).

Sichoongwe et al. (2014) concluded that relevant farm-level drivers for crop diversification include the total cultivated land area, the total output value, the types of cultivated crops, and the total input value (external and family labor, fertilizers, and technologies). In addition, diversification is also influenced by other external factors such as farmers' access to markets (proximity and distance, market information), access to extension services and information, access to credit, and networking (e.g., social networks, membership in farmers' associations) (Joshi et al., 2007; Kankwamba et al., 2012). A significant relationship between farm size and diversification was found by Pope and Prescott (1980) when they examined the determinants of farm diversification. Chavas and Aliber (1993) observed a diminishing effect of economies of scale on farm size among farmers in Wisconsin, USA. Weiss and Briglauer (2000) reported that smallholders tend to increase the degree of specialization more rapidly over time than larger farms. A significantly lower degree of diversification (i.e., a higher degree of specialization), as well as a stronger reduction in diversification over time, is also reported for businesses operated by older, less educated, part-time farm operators (Weiss and Briglauer, 2000).

Asante et al. (2018) outlined that in several empirical research studies, the estimation of diversification has been considered a joint decision-making process. Along this process, these studies employ limited dependent-variable models (e.g., the logit, probit, and tobit models and their extensions). The question of explaining the role of diversification or specialization in economic growth and development has been widely explored in economic literature using several techniques. Among them, we can enumerate the following: the index of maximum proportion, the Herfindahl index (HI), the Simpson index, the Ogive index, the Entropy index, and its associated modifications (Ibrahim et al., 2009; Ogundari, 2013). The literature, however, differentiates between the decision to diversify and the decision on how diversification occurs. There is still a need to examine whether both decisions are combined or dispersed.

In Tunisia, small mixed-farming systems hold 75–85% of agricultural land and provide more than 80% of some annual and perennial crops and livestock products (Marzin et al., 2017). Despite the important role of crop-livestock farming systems under CA in reducing the poverty of smallholders and enhancing their food security at the different levels (local, regional, and national) in the dry farming systems, the complementarities between both system components have not been appropriately explored. To our knowledge, no study has examined the impact of crop-livestock diversification under CA farming systems. Therefore, the objectives of this study are to evaluate whether a crop-livestock integrated system under CA is a complementary or rival component of mixed farming systems. This paper contributes to the existing literature on the importance of diversification and what driving factors influence diversification in livestock and integrated crop-livestock production systems under these agroecological farming systems among smallholders in Tunisian semiarid areas. Findings are expected to provide information on the determinants of diversification and whether the system components to be integrated have actual economic synergies and complementarities.

The methodology of the paper is based on a model issued from the stochastic input distance function (Villano et al., 2010; Asante et al., 2020), which explores evidence of economies of diversification and their effect on determining diversification decisions of smallholders in integrated crop-livestock systems. Our hypothesis is based on the fact that "*economies of diversification are significant in determining diversification decisions of smallholders in integrated crop–livestock systems under CA*".**[sic]** We also expect that "*economies of scale exist in these systems*", which suggests that there are opportunities to expand crop-livestock outputs without employing additional inputs or improved production technologies. Such economies of diversification are expected to be significant among the potential existing output combinations (cereals and forage crops with other crops and other crops with livestock) in integrated crop-livestock systems under CA farming.

## Reasons for crop-livestock integration and diversification under CA farming systems

Complementary relationships between CL farming activities have been documented in many studies (Tilman et al., 1996; Loreau, 1998; Yachi and Loreau, 2007). In fact, the synergy degrees may vary spatially and temporally, even within the same agroecological system. Tarawali et al. (2004) suggested that the diversification of farming systems secures synergies between crop and livestock production, improves productivity, and ensures the resilience of integrated agricultural production systems. Moreover, it has been argued that these mixed-farming systems allow smallholders to expand their sources of foods and staples in household diets (diet diversification) and empower them to actively access local markets for high-value products (FAO, 2010).

Martin et al. (2016) identified the different forms of CL integration, summarized as follows: *global coexistence* is the transfer of raw materials (e.g., forage and organic manure) among farms through the national or global market; this first form of integration does not include direct coordination between farmers since it is based on a spatial and temporal partition of crop and livestock production; *local coexistence* happens when a local organization (agricultural cooperative) ensures the coordination among farmers by transferring the raw materials; *complementarity* is the direct and frequent coordination between farmers, allowing an exchange of raw materials between farms.

Guesmi et al. (2019) claimed that adopting integrated crop-livestock systems under CA is beneficial for two reasons: (i) mulch left on the soil surface can be used as animal fodder; and (ii) permanent vegetative cover with a high level of nutrients improves animal performance. However, competition between crops and livestock may occur. According to Guesmi et al. (2019), in a region where livestock production is the main activity, crop-livestock integration seems inappropriate for CA adoption, although the CL combination offers farmers a more diverse source of food and income-generating options. Adopting a CA system that requires leaving mulch on the soil surface can reduce the quantity of feed for livestock. Some suggestions for successful CL integration refer to either introducing crops with higher biomass production or adapting herd size to forage production capacity or developing alternative feeding options (Ameur et al., 2021). In the literature, much has been written and published on the trade-offs that smallholder farmers face when having to allocate their biomass resources among competing objectives such as feed for animals or mulch (Klapwijk et al., 2014). In natural resource-limited systems (e.g., dry land farming systems) and environments, farmers prioritize the livestock feeding option over soil amendment to improve soil quality (Tittonell et al., 2015). This could be explained by the limited availability of fodder for livestock in these systems which, therefore, often results in constant rivalry for the use of the limited crop residues.

Masmoudi (2012) estimated the effect of crop-livestock integration under direct seeding. Their work shows that grazing integration within the practice of direct seeding is possible considering light and moderate grazing intensity, as long as vegetation cover remains greater than 78% before grazing. Along these lines, Byrnes et al. (2018) argued that grazing management, under no-till, can significantly influence soil quality and health; however, a controlled grazing strategy during the dry season will be a central component of the livestock feed biomass strategy under this mixed farming system. Moujahed et al. (2015) assessed the effect of stocking rate on the variation of stubble biomass and lamb growth. Their results show that the stocking rate decreased in some plots due to animal preferences while grazing. The variation in the chemical composition of stubble is thus suggested to be related to the selective grazing behavior of lambs.

Landers (2007) enumerated the benefits of crop-livestock integration under CA based on no-tillage. The simultaneous implementation of CA principles such as crop diversification allows enhanced forage production for livestock, which is also a source of organic matter and crop fertilization. Other benefits of integrated crop-livestock systems under CA based on no-tillage follow: (i) increased profit through reduced production costs; (ii) reduced disease, pest, and weed pressures on crops; and (iii) maintaining a high stocking rate on rotated pastures (Landers, 2007). The author claimed that the benefit of crop-livestock integration under CA is higher compared to the benefits of crop and livestock systems conducted separately. Landers (2007) also focused on the technical and financial aspects of the integrated crop-livestock system under CA by comparing case studies with and without CA interventions in the Brazilian context. Results showed that adopting integrated crop-livestock systems under CA based on no-tillage improve the situation of winter pastures for cattle, thus leading to a higher income. Other effects of adopting integrated crop-livestock systems under CA are as follows: (i) improved herd performance; (ii) enhanced pasture stocking levels (from 1 to 1.76 AU/ha); (iii) a 10% increase in soybean and maize yields; and (iv) 63% more annual net profit. The adoption of integrated crop-livestock systems under CA also led to a remarkable variation in deforestation, which has been estimated through the proportions of the crop to pasture and variations in cumulative stocking rates. Results of the financial analysis of several case studies indicated a remarkable financial benefit in terms of internal rate of return and net present value. Other similar studies showed that CA-based systems in Zambia generated an increase of up to 33% in grain yields and consequently a greater net benefit (Komarek et al., 2019).

Agriculture diversification includes different stages (Chaplin, 2000; Vyas, 2006). As quoted by Chaplin (2000), "*the process of diversification of agriculture may pass through four stages: i) At the first stage the cropping system shifts from monoculture to multiple cropping. This phenomenon generally occurs in the developing countries and most of the third world countries are under this category; ii) At the second stage the farmers start more than one enterprise. For example, crops and animal husbandry, beside the number of crops in a year is more than one; iii) Thirdly, initiation of mixed farming. In the last stage of diversification, the activities which are incorporated are beyond the agricultural domain such as adding the value through the processing, packaging and producing by products*". **[sic]**

CL diversification refers to the combination of the production of one or more crops and livestock with the available resources (Komarek et al., 2019). Diversification is determined by multiple factors, including per capita income, the number of crops cultivated, livestock structure, and the total value of outputs. Through an assessment of diversification indices, Komarek et al. (2019) argued that the CL diversification index is greater than the separate indices for crop diversification and livestock diversification. Results also revealed that income stability, access to extension services, and market information contribute significantly to increasing crop-livestock diversification and allowing farmers to meet market requirements and increase their profitability from farming (Mesfin et al., 2011). By analyzing the status quo of the crop-livestock farming system practiced in Swaziland, Mhazo et al. (2010) admitted that adopting an integrated crop-livestock farming system is part of a context of food security insurance and increasing productivity. Liniger et al. (2011) confirmed that an integrated CL farming system contributes to productivity enhancement and water use efficiency improvement. Their findings revealed that the adoption of a mixed-farming system generates a 50% improvement in productivity and farm income in Ethiopia.

## Conceptual framework and modeling approach

### Analytical framework—Theoretical input distance function model

Economic diversification is an essential aspect of sustainable development in dryland regions, which are one of the most sensitive areas to climate change and human activities, as diversification enhances production stability and promotes structural and long-term transformations toward more adaptive farming systems in these regions. According to Villano et al. (2010), these aspects have been investigated using two main approaches: econometric methods and accounting-based profitability measures. The first approach focuses mainly on using the distance function. However, the second approach, the accounting-based profitability approach, has been predominantly employed in investigating economies of diversification between firms and is not appropriate for examining complementarities between and within farm activities (e.g., cereals, legumes, fodder crops, and livestock). Economies of diversification appear when the diversion of the farming system leads to a decrease in costs associated with several outputs produced simultaneously with a set of input combinations (Baumol, 1982). In such a case, smallholder farmers decide to diversify because they expect that synergies obtained from these enterprises could contribute to enhancing their economies of diversification and reduce production risks given the CC threats (Chavas and Aliber, 1993; Paul and Nehring, 2005; Villano et al., 2010). Similarly, there is considerable evidence of the productivity impacts of diversification and climate change linkages as diversification contributes to protecting and improving agricultural and livestock production. This would reinforce and sustain farming productivity and consequently stabilize the volatility of food prices (Coelli and Fleming, 2004; Rahman, 2009; Tibesigwa et al., 2015; Abdulai and Abdulai, 2017). Several studies have explored the economies of diversification in smallholder farming systems and the degree of complementarities between inputs and outputs in the economic performance of diversified farm households (Pope and Prescott, 1980; Weiss and Briglauer, 2000; Coelli and Fleming, 2004; Chavas and Kim, 2007, 2010). The limitation of these empirical studies is that only agricultural diversification in terms of crop production has been examined. The studies dealing with the analysis of livestock diversification or integrated crop-livestock diversification are limited, especially under CA framing systems. Following this premise, it is important to assess crop-livestock integration and diversification and the driving forces contributing to strengthening this integration and diversification and, thus, increasing livestock-based production to meet the demands of the rural communities and consequently the growing Tunisian population. In this study, we applied the distance function approach (Coelli and Fleming, 2004; Villano et al., 2010) to assess diversification economies in mixed crop-livestock production systems operating under CA.

This distance function approach has been frequently used to assess economies of diversification in agricultural farming systems (Chavas and Aliber, 1993; Paul and Nehring, 2005; Rahman, 2009). The distance function approach was first proposed by Shephard (1953). The concept of this function is used to describe and model multiple outputs and inputs in the same production technology framework (Villano et al., 2010). A distance function is characterized by its double possible orientation—output or input orientation (Villano et al., 2010). When an output distance function is considered, a maximal level of outputs for a fixed level of inputs is considered. Whereas a fixed level of outputs for a minimal level of inputs is considered if we select an input distance function, the concept of the theoretical model planned to be used and named as an input distance function is illustrated by considering using a vector of input combinations X to produce a vector combination of outputs Y.

An input distance function is a function of the inputs (X) that produce outputs (Y). An input distance function includes the scaling of an input vector and is defined on the input set, L(Y), as follows:

$$D(X, Y) = \max\{\rho : \left(\frac{X}{\rho}\right) \in L(Y)\} \tag{1}$$

where

- L(Y) is defined as the set of all input vectors, X, which can produce output vector Y.

- D(X, Y) is a distance function which assumed to be non-decreasing, positively linearly homogeneous and concave in X, and increasing in Y (Coelli and Perelman, 2000).
- D(X, Y) $\geq$ 1 if the input vector X belongs to the feasible input set L(Y).
- $\rho$ is the scalar "distance" by which the output vector can be deflated.

## Empirical model

### Model specification

Given that complementarities between crops and livestock (i.e., sheep) occur when additional output (i.e., forages) is generated jointly with other outputs as a combined production system rather than operating the enterprise elements as separate systems, and that inputs are generally fixed by smallholder farmers in dryland areas in general, and in Tunisia in particular, we focused the empirical analysis in this study on the input orientation production technology (Coelli and Perelman, 2000; Coelli and Fleming, 2004; Villano et al., 2010; Asante et al., 2020). Applying an input orientation function allows a description of the specification of the production function, an estimation of technical efficiency, and an assessment of the complementary synergies and/or competition between the generated outputs (both crops and livestock). However, this complementary function does not guarantee the existence of economies of scope. According to Chavas and Kim (2007, 2010), the complementarities conditions are not generally necessary nor sufficient for economies of scope.

To measure complementary synergies and/or competition, derivates from second-order cross-partial analysis of the output variables in an input distance function are used in the empirical analysis. This is suggested by the fact that there are already several production possibilities generated from the nature of this frontier function (i.e., the curvature of the input distance function). This will allow the estimation of the first order and cross-output elasticities. A parametric method is applied using the *translog* functional form:

$$\begin{aligned}\ln D\,(X_i, Y_i) &= \alpha_0 + \sum_{j=1}^{4} \alpha_j \ln X_{ji} + 0.5 \sum_{j=1}^{4} \beta_j \ln Y_{ji} \\ &+0.5 \sum_{j=1}^{4} \sum_{k=1}^{4} \alpha_{jk} \ln X_{ji} \ln Y_{ki} + 0.5 \sum_{j=1}^{n} \sum_{k=1}^{m} \beta_{jk} \ln Y_{ji} \ln Y_{ki} \\ &+0.5 \sum_{j=1}^{n} \sum_{k=1}^{m} \omega_{jk} \ln X_{ji} \ln X_{ki} \qquad (2)\end{aligned}$$

where

- In the four considered inputs, D ($X_i$, $Y_i$) is the input distance function assumed to be non-decreasing, concave, and positively linearly homogeneous;
- $X_{1i}$, $X_{2i}$, $X_{3i}$, and $X_{4i}$ are the inputs used in this function, which are the values of labor (expressed in person-days per year), land (in hectares), crop capital (in value), and livestock capital (in value), respectively;
- $Y_{1i}$, $Y_{2i}$, $Y_{3i}$, and $Y_{4i}$ are the outputs used in this function, which represent the values in Tunisian dinars (TND) of the four outputs of cereals (e.g., wheat), forage crops, legumes, and livestock, respectively;
- i is the ith sample farmer used in the agricultural production function.

Paul and Nehring (2005) argue that the choice of orientation (output or input) depends on two factors: the purpose of the undertaken study and the fixity levels for both outputs and inputs. Within the same theme, we considered the following hypothesis based on the methodological framework of Paul and Nehring (2005):

- –ln D(X, Y) = $\upsilon$ – u;
- Input restrictions must be homogeneous to the degree of +1.
- Consider the labor ($X_{1i}$) factor (input) to normalize the input vectors;
- All restrictions required for symmetry and homogeneity conditions are:
  - $\alpha_{ij} = \alpha_{ji}$ i, j = 1, 2, …, n (n = 4)
  - $\beta_{ij} = \beta_{ji}$ i, j =1, 2, …, m (m = 4)

$$\circ\ \Sigma\alpha_{ij} = 1. \qquad (3)$$

The established conditions above led to the empirical model for estimation, specified as follows:

$$\begin{aligned}-\ln D\,(X_i, Y_i) &= \alpha_0 + \sum_{j=2}^{4} \alpha_j \ln(\frac{X_{ji}}{X_{1i}}) + \sum_{j=1}^{4} \beta_j \ln Y_{ji} \\ &+0.5 \sum_{j=2}^{4} \sum_{k=1}^{4} \alpha_{jk} \ln(\frac{X_{ji}}{X_{1i}}) \ln Y_{ki} + 0.5 \sum_{j=1}^{n} \sum_{k=1}^{m} \beta_{jk} \ln Y_{ji} \ln Y_{ki} \\ &+ 0.5 \sum_{j=2}^{n} \sum_{k=2}^{m} \omega_{jk} \ln(\frac{X_{ji}}{X_{1i}}) \ln(\frac{X_{ki}}{X_{1i}}) + \nu_i + u_i \qquad (4)\end{aligned}$$

where

- $\upsilon_i$ by hypothesis is supposed to be an independently and identically distributed normal random error with a mean of zero and a variance of $\sigma^2_{\upsilon}$;
- $u_i$ is a nonnegative technical inefficiency effect that is expected to be independently distributed and have a truncated-normal distribution;

- $u_i$ is defined following Battese and Coelli (1995) where the truncation (at zero) of the normal distribution with a mean of $u_{i,}$ and a variance of $\sigma_{\upsilon}^2$, specified as follows:

$$\mu_i = \delta_0 + \sum_{k=1}^{7} \delta_k z_{k_i} \tag{5}$$

where

- $Z_{1i}$ denotes the i$^{th}$ farmer's age, in years;
- $Z_{2i}$ is an education dummy variable that is 1 if the i$^{th}$ farmer has completed at least six years of schooling, and 0 (zero) otherwise;
- $Z_{3i}$ is defined as the dependency ratio value for the i$^{th}$ farmer's household (it is calculated as the number of dependent members divided by the total household size);
- $Z_{4i}$ is defined as the percentage of off-farm income relative to total farm income (the total farm income includes the value of outputs for the i$^{th}$ farmer);
- $Z_{5i}$ is a credit dummy variable for the i$^{th}$ farmer (this value is 1 if the i$^{th}$ farmer obtained credit, and 0 otherwise);
- $Z_{6i}$ is as an extension dummy variable for the i$^{th}$ farmer (this value is 1 if the i$^{th}$ farmer received extension services support or advice, and 0 otherwise);
- $Z_{7i}$ is defined as the HI value of mixed crop-livestock diversification for the i$^{th}$ farmer;
- δ is considered an unknown parameter. The coefficients of these parameters will be estimated to explain the inefficiencies of production of the farm output activities (e.g., cereals, legumes, forage crops, and livestock);
- i: 1, …, N (number of farmers considered in the empirical analysis).

The two models in Equations (4) and (5) are simultaneously estimated using Stata econometric software version 14.

## Qualitative assessment of crop-livestock activity diversification: HI

To assess the degree of specialization for the sample of CA smallholder adopters, we use HI defined as follows:

$$HI = \sum\nolimits_{j=1}^{n} S_j^2 \tag{6}$$

where

- n is the number of farming products (e.g., field crops, cereals, and livestock);
- $S_j$ is defined as the jth farm product share value in the total output of the considered farm;
- In the empirical analysis, it is considered that HI is defined by its minimum value which is 1/n. This suggests that minimizing HI subject to the sum of the shares is to be one. Thus, given $S_j = 1/n$, for all j = 1, 2, …, n, this indicates a full diversification, with all the farm outputs having the same share (1/n);

The HI ratio ranges from zero to one. The value of one indicates complete specialization (i.e., only one activity). Under the hypothesis of having a high level of diversification, the value of the HI is likely to be small. Based on this hypothesis, the sample farmers were categorized into three groups, namely, diversified, highly specialized, and moderately specialized, based on the value of HI. Thus, if HI $\leq$ 0.5, this suggests a diversification between crop and livestock products. When the HI of a smallholder is $>$ 0.8 they are considered highly specialized, and moderately specialized if 0.8 $>$ HI $>$ 0.5.

## Qualitative evaluation of complementary synergies and/or substitute rivalries in crop-livestock under CA farming systems

From a theoretical perspective, we expect a negative sign for the first derivative of the distance function displayed in Equation 4 for all outputs considered in the empirical analysis. This suggests that producing an additional unit of output while maintaining all the rest of the other variables unchanged will affect the input needs that will be reduced to ensure the efficiency of the production function (Coelli and Fleming, 2004; Rahman, 2009). However, a positive sign is expected in the second derivative of the distance function for all four outputs, suggesting evidence of complementary synergies (Villano et al., 2010). Economic diversification for farmers operating under CA is inextricably linked with the structural transformation of their economies and the achievement of higher levels of productivity resulting from the movement of economic resources within and between selected outputs j and k ($j \neq k; j, k = 1, 2, 3, 4$). It exists if the following equation is validated:

$$\frac{\partial^2 D}{\partial Y_j \partial Y_k} > 0,\ j \neq k; j, k = 1, 2, 3, 4. \tag{7}$$

Following Villano et al. (2010) and Asante et al. (2020), the concept of complementary synergies has been used in this paper. This suggests that all derivatives (i.e., second order and cross-partial) do not automatically indicate the existence of an economic gain for the smallholder farmer. A positive value indicates the presence of diversification economies, but it is a necessary and not sufficient condition. On the contrary, diversification diseconomies are confirmed by a negative value under a necessary and sufficient condition outlining a high level of competition between farm activities (i.e., livestock and crops). In the empirical application, we considered the following rule: the second partial derivative concerning the logarithms of two involved outputs is equal to the corresponding coefficient of the interaction between these defined outputs.

In this case, we estimated the following values and examined to what extent these values are statistically significant (i.e., testing if they are different from zero) for the considered outputs:

$$\beta_{jk} = \frac{\partial^2 \ln D}{\partial \ln Y_j \partial \ln Y_k} \; j \neq k; j, k = 1, 2, 3, 4 \qquad (8)$$

Where:

$\beta_{jk}$ is defined as a cross-product coefficient.

If the sign of this coefficient is positive, the two outputs show complementary synergies in their production process (Asante et al., 2020).

If the sign is negative, the two outputs are considered substitutes.

The equation displayed in Equation 7 illustrates that the coefficient issued from the cross-partial derivative of this equation is equal to the coefficient of Equation 8 multiplied by the reciprocals of the values of the two involved outputs, $Y_j$ and $Y_k$. From the stochastic input distance function, we used the standard errors of the $\beta_{jk}$ coefficients. This was used to test the null hypothesis (no synergies) against an alternative hypothesis of synergies, taking into consideration the assumption of input homotheticity, which requires the input isoquant to expand or contract radially in the input distance function (i.e., production function). In the empirical model, we expect to have six output combinations associated with the four activities used to assess the complementary synergies or substitution (e.g., specialization) between these activities.

## Data sources and specification of the model variables

The data used in this study have been collected from smallholder crop-livestock farmers operating under CA systems who were part of the CL integration under the CA project[1] funded by the International Fund for Agricultural Development (IFAD) under agreement number #200116. These farmers were selected randomly from those who benefited from the project programs and innovation packages aimed at crop-livestock integration under CA. The farms in this study are rainfed and located in the arid areas of four governorates in the north of Tunisia: Zaghouan, Beja, Siliana, and Kef. From a total of 100 farmers (who had interventions from the CLCA project), we retained only 59 farmers for two reasons: (i) farmers who had interventions from the project; and (ii) full data completed with these farmers. The data collection process was conducted during the last quarter of 2021, with the country still under lockdown due to COVID-19. The farmers sought to improve their farming systems by enhancing their farming practices through the adoption of a CA component or package (e.g., no-till, residual biomass, forage mixtures, and crop rotation). The data were obtained by using structured questionnaires with pre-identified smallholders. The collected data include socio-demographic and economic information such as technical information on both crop and livestock activities, types of crops and livestock produced, the value of production for both activities, and other household characteristics. Table 1 presents summary statistics (means) for the variables used in the empirical model.

TABLE 1 Characteristics of sample households—socio-demographic variables used in the empirical model.

| Variables | Mean | Max | Min | SD |
|---|---|---|---|---|
| **Outputs** | | | | |
| Cereals (TND)[a] | 1,806.10 | 3,936 | 560 | 812.53 |
| Legumes (TND)[b] | 1,216.40 | 2,900 | 440 | 584.91 |
| Forage crops (TND)[c] | 1,247.10 | 2,750 | 450 | 720.30 |
| Livestock 1 (cattle) (TND) | 17,516.70 | 69,600 | 2,700 | 25,842.48 |
| Livestock 2 (small ruminants) (TND) | 47,618.3 | 190,500 | 5,000 | 52,403.11 |
| **Inputs** | | | | |
| Labor (person-days per year) | 27.20 | 188 | 2 | 38.60 |
| Land (hectares) | 81.40 | 400 | 4 | 87.26 |
| Crop capital (TND)[d] | 2,040.10 | 4425 | 214 | 1,102.26 |
| Livestock capital (TND)[e] | 14,722.20 | 51,000 | 3,000 | 11,836.92 |
| **Inefficiency variables** | | | | |
| Age of household (years) | 51.40 | 70 | 34 | 9.90 |
| Education (Yes = 1, No = 0) | 0.90 | 1 | 0 | 0.30 |
| Dependency ratio | 0.60 | 1 | 0.11 | 0.20 |
| Share of off-farm income (%) | 90.50 | 100 | 36.12 | 28.14 |
| Credit access (Yes = 1, No = 0) | 0.08 | 1 | 0 | 0.22 |
| Extension services access (Yes = 1, No = 0) | 0.95 | 1 | 0 | 0.00 |
| Herfindahl index (HI) | 0.69 | 1 | 0.14 | 0.30 |

[a]Cereal crops are composed of wheat; [b]Forage crops are composed of barley, oats, and other crops; [c]Crop capital (which combines all costs used in the production of crops excluding expenses on land and labor); and [d]Livestock capital (which combines all costs used in livestock production excluding expenditures on breeding, labor, feed, and veterinary services).

1 TND = 0.33 USD (January-September 2022 average).

Source: own elaboration from field data (2022).

The statistical analysis shows that the major crops cultivated by farmers are cereals (especially wheat), legumes, and forages

---

[1] See https://mel.cgiar.org/projects/clca2 for more information about the project.

(barley, oats, and other forage crops), with their contributions to the total crop value representing 42, 28.5, and 29%, respectively (Table 1). Major livestock includes small ruminants (73%) and cattle (27%). The average value of cereals (e.g., wheat) produced is 1,806.1 TND/year, and legumes and forage crops have an average of 1,216.4 and 1,247.1 TND/year, respectively. The mean value of small ruminant output is 47,618.3 TND/year. On average, cattle output is 17,516.7 TND/year. Over the course of one cropping season, an average of 27.2 person-days is used for crop-livestock production. The average capital used in crop activities is 2,040.1 TND/year. The average amount of capital used for livestock production is 14,722.2 TND, representing 88% of the total farm costs.

## Empirical results and discussion

In our empirical model specification in Equation 4, labor has been used to normalize input $X_1$ so that all other inputs are represented relative to it. Following Singbo et al. (2021), all variables (both inputs and outputs) have been mean-corrected before estimation, where each output and input variable has been divided by its geometric mean. This suggests that the coefficients of the first order terms can be directly interpreted as distance elasticities evaluated at the geometric mean of the data.

### Degree of enterprise diversification and/or specialization in integrated crop-livestock systems under CA farming systems

The findings from the HI analysis are shown in Figure 1, which presents farmer distribution according to the degree of enterprise specialization.

A high percentage of the smallholders (37%) are indeed diversified (HI $\leq$ 0.5) (Figure 1). Around 15% of farmers have a moderate level of specialization (HI of 0.5–0.8) (nine smallholders). Highly specialized smallholders under CA farming systems accounted for around 48% (28 smallholders). In general, there are two major types of farms: 37% are diversified, and 48% are rather specialized. These findings suggest a further examination into the extent to which economies of diversification may be a strategy for increasing farm productivity which has a direct impact on the food security of smallholders in semiarid areas.

### Estimated model and empirical results

Given that all variables considered in the analysis (input and output) are estimated in log values and normalized by their respective sample means, the parameters from the input distance function have been interpreted as direct elasticities at the sample mean. The first order estimates of coefficients for these inputs and outputs are presented in Table 2. The sign and magnitude of these coefficients (e.g., input and output elasticities) are expected, and most are statistically significant.

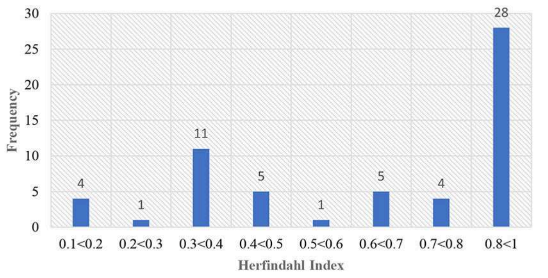


FIGURE 1
Degree of diversification of crop-livestock activities in integrated crop-livestock under the CA farming system (HI, Herfindahl index). The following classification is used: if HI $\leq$ 0.5, this suggests diversified crop-livestock smallholders; HI >0.8 indicates highly specialized smallholders, and HI of 0.5–0.8 indicates moderately specialized smallholders. Source: Own elaboration from field data (2022).

Two input variable coefficients are positive. They are also significant at a 5% level. The highest input elasticity is for labor (0.74) followed by crop capital (0.30), land (0.27), and livestock capital (−0.31). The elasticities of input variables are interpreted as the percentage change in an input variable that is required to support a 1% change in the output variables. For example, an increase of 0.74% in labor is required to generate a 1% increase in all outputs, and a 0.27% increase in land is the minimum required for a 1% increase in all outputs.

In terms of outputs, there are positive and negative estimated coefficients. Given the high importance of forage crops among the farm activities in this CL farming system, forage crop output has the highest significant elasticity of 0.53, followed by cereals (e.g., wheat) with a significant elasticity of 0.26. That is, an increase of 1% in the forage crop output level suggests an increase of 0.53% in all inputs to sustain it. The same trend is evident for wheat, with a 1% increment in this crop requiring an increment of 0.26% in all inputs. These results indicate that the production of forage crops and wheat, on top of legumes and livestock, plays a significant role in integrated CL production under CA farming systems in Tunisian dryland areas.

The estimated coefficients of legume and livestock outputs are negative (−1.1 and −0.54, respectively).

This means that a decrease in labor use led to reducing the production levels of those two outputs (legumes and livestock).

Given that output elasticity (i.e., the elasticity of scale) measures the change in percentage change of output driven by a percent change in the use of all inputs, the total value of all output elasticities, −0.85, is thus considered the "valued

TABLE 2 Empirical coefficients of the stochastic input distance function (including inefficiency coefficients).

| Estimated variables[a] | Estimates | Standard deviation | *t*-values[b] |
|---|---|---|---|
| Input distance function model | | | |
| Intercept | 0.99 | 0.13 | 7.19 |
| Land | 0.27 | 0.09 | 2.82 |
| Crop capital | 0.30 | 0.25 | 1.57 |
| Livestock capital | −0.31 | 0.41 | −0.75 |
| Cereals | 0.26 | 0.35 | 1.72 |
| Legumes | −1.10 | 0.49 | −2.24 |
| Forage crops | 0.53 | 0.62 | 1.85 |
| Livestock | −0.54 | 0.40 | −0.13 |
| (Land)$^2$ | −0.77 | 0.13 | −0.56 |
| (Crop capital)$^2$ | −0.27 | 0.16 | −1.68 |
| (Livestock capital)$^2$ | 0.22 | 0.73 | 0.30 |
| (Land × Crop capital) | 0.31 | 0.43 | 0.74 |
| (Land × Livestock capital) | −0.15 | 0.36 | −0.41 |
| (Crop capital × Livestock capital) | −1.09 | 0.62 | −1.75 |
| (Cereals)$^2$ | −1.98 | 0.86 | −2.29 |
| (Legumes)$^2$ | −0.88 | 0.95 | −0.92 |
| (Forage crops)$^2$ | −4.11 | 0.95 | −4.31 |
| (Livestock)$^2$ | 0.16 | 0.54 | 0.29 |
| (Cereals × Legumes) | 0.16 | 1.02 | 1.62 |
| (Cereals × Forage crops) | 2.84 | 0.97 | 2.91 |
| (Cereals × Livestock) | 0.13 | 1.01 | 0.13 |
| (Legumes × Forage crops) | −1.01 | 1.01 | −1.00 |
| (Legumes × Livestock) | −2.31 | 0.93 | −2.48 |
| (Forage crops × Livestock) | 0.56 | 0.97 | 1.57 |
| (Land × Cereals) | 0.45 | 0.63 | 0.65 |
| (Land × Legumes) | 0.39 | 0.75 | 0.52 |
| (Land × Forage crops) | 0.97 | 0.77 | 1.26 |
| (Land × Livestock) | 0.46 | 0.39 | 1.51 |
| (Crop capital × Cereals) | −1.93 | 0.84 | −2.30 |
| (Crop capital × Legumes) | −1.79 | 0.70 | −2.55 |
| (Crop capital × Forage crops) | −0.55 | 0.82 | −0.67 |
| (Crop capital × Livestock) | −0.19 | 0.50 | −0.39 |
| (Livestock capital × Cereals) | 0.022 | 0.97 | 0.022 |
| (Livestock capital × Legumes) | 2.60 | 1.01 | 2.58 |
| (Livestock capital × Forage crops) | 1.27 | 1.11 | 1.15 |
| (Livestock capital × Livestock) | −2.39 | 8.33 | −2.87 |
| *Inefficiency effects model* | | | |
| Intercept | −2.41 | 0.776** | −3.10 |
| Age | 0.007 | 0.0045* | 1.63 |
| Education | 0.39 | 0.15** | 2.65 |
| Dependency ratio | −0.023 | 0.38 | −0.06 |
| Share of off-farm income | 2.55 | 0.84** | 3.02 |
| Credit access | −0.52 | 0.15** | −3.51 |
| Extension access | −0.09 | 0.17 | −0.56 |
| Herfindahl index of diversification | −0.16 | 0.13* | −1.55 |
| *Variance parameters* | | | |
| σ$^2$ | 0.031 | 0.007 | 4.13 |
| γ | 0.44 | 0.10*** | 4.43 |
| Loglikelihood function | | 21.95 | |
| Likelihood-ratio statistic test | | 22.04*** | |

[a] The variable Land used in the analytical model is defined as ln[land/labor] where the homogeneity assumption imposed on inputs, following Coelli and Perelman (2000) and Asante et al. (2020) as shown in Equation 4. The two remaining input variables are similarly defined.

[b] *, **, ***Significant at 10, 5, and 1%, respectively.

Source: own elaboration from model results (2022).

elasticity of scale”. The value of this elasticity, in our case, is less than a unit and negative, indicating a strong decreasing return to scale (the efficiency of operation would increase if we increased the land size in our sample). This result seems to corroborate the evidence of economies of scale in integrated CL farming systems in the Tunisian rainfed context, suggesting that opportunities exist to expand crop-livestock outputs with better management of production inputs or improved CA technologies.

## Technical inefficiencies in crop-livestock production under the CA farming system

Factors affecting technical inefficiency scores in CL farming systems are displayed in Table 2. Most of the coefficients of these factors are significantly correlated with the technical inefficiency of CL farms. The calculated value of the $\gamma$ parameter (the technical inefficiency effect), a considerable element of the total variability of crop-livestock production under CA, is positive (0.44) and significant at $P < 0.01$.

However, before we proceed to discuss the parameters of the z-variables in the inefficiency models, we tested the null hypothesis that these coefficients are all zero and do not contribute to the explanation of the distribution of the inefficiency effects. The calculated test statistic value for this joint significance is 22.04 and it is significant at $P < 0.05$. The test statistic ratio is about 20.28 for an upper 0.5% point for the $\chi^2$ distribution with seven degrees of freedom. This suggests the non-acceptance of the null hypothesis that the coefficients of the z-variables in the inefficiency model are all zero. In this case, we retained the alternative hypothesis that all considered variables will contribute, at different weights, to explaining the inefficiency effects distribution.

The positive significant coefficients of age, education, and share of off-farm income variables are significant at 10, 5, and 1%, respectively. These results suggest that higher farmer age, education level, and share of off-farm income led to higher technical efficiency in CL production under CA (Latruffe et al., 2004; Hadley, 2006; Theodoridis et al., 2014). They provide evidence that age and education are potential factors in efficiency (Karimov, 2014). Hadley (2006) revealed that younger farmers can be more inclined to adopt innovative input-saving technologies. In contrast, older farmers are more efficient in managing farming risks since they can rely on longer practical experience in addressing inefficiency-related risks. A positive correlation also exists between off-farm income and technical efficiency. This suggests that the higher the off-farm income is, the more likely the farm will be technically efficient. This can be explained by the fact that farmers with higher off-farm income have greater investment capacity in terms of mechanization, better and more timely access to necessary farming inputs, and so on (see Frelat et al., 2016). These farmers do have a "buffer capacity", which allows them to cope with shocks in more effective ways. It is important to note here that farmers' coping capacities are not only determined by their financial situation, and that more social and organizational factors are crucial in this regard. The significant negative coefficient of HI indicates that greater specialization (i.e., lower diversification) is more likely to be associated with higher scores of technical inefficiencies in CL integration under CA. This explains that diversification may lead to tangible benefits by increasing income through the adoption of sustainable intensification and diversification strategies.

The non-significant negative impact of the dependency ratio on technical efficiency reveals that households with a high dependency ratio are more likely to be less efficient. This could be because the number of dependent family members (economically inactive) increases and the household must allocate more financial resources for their basic needs (food, health, education, etc.) and other expenses. A high dependency ratio causes less productivity for labor, which results in a high consumption expense level and less output production. The consequence is that fewer resources might remain for farming (use of good inputs for cropping, livestock management, feeding, etc.). This fact is materialized at the household level, where families cannot afford to use improved agricultural technologies such as fertilizers and improved seed varieties (Asefa, 2011).

TABLE 3 Frequency distribution of technical efficiency for CA adopter smallholders.

| Classes | Class 1 (< mean) | Class 2 (> mean) |
|---|---|---|
| Mean technical efficiency/class (%) | 59.20% (62.7%) – SD = 0.05 | 83.80% (37.30%) – SD = 0.105 |
| Average net income (TND) | 48,285.99 | 62,796.16 |
| Average land area (Ha) | 96.70 | 55.63 |
| Average livestock capital (TND) | 14,492.79 | 15,108.08 |
| Mean technical efficiency (%) | 68.40% (SD = 0.14) | |

The numbers displayed in parentheses denote the percentage of CA-adopting smallholder farms in each defined technical efficiency class/typology.
SD: standard deviation.
1 TND = 0.33 USD (January–September 2022 average).
Source: own elaboration from model results (2022).

The negative effect of access to credit on technical efficiency suggests that farmers with lower access to this service are technically less efficient. This confirms the importance of access to credit services for crop-livestock smallholders operating under CA. Credit can help in acquiring inputs (e.g., machinery and forage seed) and labor at less cost and shorter time (e.g., improving farmers' productivity) and increasing technical efficiency. Regarding access to extension services, although the coefficient is negative, it is not significant. Therefore, the literature confirms the essential role of extension services in technology transfer to smallholders and knowledge sharing and how this service increases technical efficiency (Asante et al., 2020).

The computed average technical efficiency of crop-livestock production under the CA farming system is estimated at 68.40%, with a range of 47.80–98.60%. Taking the present state of technology and the current input-output mix, this suggests that farms in the sample can increase their output by about 31.60% without changing their levels of input use (Table 3). The frequency distribution of technical efficiency across the sample is also presented in Table 3. Estimated efficiency measures reveal that 37.30% of the farms in the sample are relatively more efficient than the sample average efficiency level, with an efficiency score >83.40%, and 37 smallholder farms (62.70% of the total sample) having a mean efficiency of <59.20%.

The findings in Table 3 suggest a strong correlation between land and livestock holding and technical efficiency. The TE increases with livestock capital and decreases with land area.

TABLE 4 Frequency distribution of technical efficiency according to HI clusters for CA adopter smallholders.

| Technical efficiency classes | $HI \leq 0.50$ Diversified crop-livestock enterprises | $0.50 < HI \leq 0.80$ Moderately specialized crop-livestock enterprises | $HI > 0.80$ Highly specialized crop-livestock enterprises |
|---|---|---|---|
| Mean technical efficiency/class (%) | 69.13% (SD = 0.14) | 79.30% (SD = 0.15) | 62.20% (SD=0.102) |
| Mean technical efficiency (%) | | 68.40% (SD = 0.14) | |
| Mean HI/class (%) | 32.90% (SD = 0.108) | 68.55% (SD=0.03) | 96.50% (SD=0.05) |
| Mean HI (%) | | 69.10% (SD = 0.29) | |
| Average net income (TND) | 68,503.08 | 23,956.26 | 48,116.58 |

Numbers displayed in parentheses denote the percentage of CA adopter smallholder farms in each HI cluster.
SD, standard deviation.
The Mann–Whitney test (Banker et al., 2010) was used to evaluate the significance between the three clusters.
1 TND = 0.33 USD (January–September 2022 average).
Source: own elaboration from model results (2022).

The results for the estimates of technical inefficiency with land holding and livestock capital depict: farmers with an average TE less than average in the sample (class 1) are with an average of 96.70 ha and 14,492.79 TND, and farmers with a TE greater than average in the sample (class 2) are with an average of 55.63 ha and 15,108.08 TND. This suggests the positive impact of livestock capital on TE.

This section focuses on assessing the impact of crop-livestock diversification on farm-level technical efficiency. Summary statistics of diversified and less-diversified farms are reported in Table 4. The farms in the sample are divided into three sub-categories: diversified, moderately specialized, and highly specialized crop-livestock enterprises. These are classified according to what their HI means.

Summary analysis shows significantly higher technical efficiency scores for more diversified farms compared to more specialized farms (average technical efficiencies of 69.13 and 62.20%, respectively) (Table 4). The Mann–Whitney test (Banker et al., 2010) shows a z-statistic of 2.062 with $P = 0.039$, indicating a significant difference between the three technical efficiency clusters (Table 4). In addition, the mean technical efficiency is significantly greater for the moderately specialized (79.30%) compared to the highly specialized crop-livestock smallholders (62.20%), with a z-statistic of 2.81 and $P = 0.00496$. This can be explained by the fact that diversified enterprises in the study area are usually small in size and are managed by households that try to secure their livelihoods through small-scale diversification primarily devoted to daily income and consumption support. Thus, the scale of operation of these farms and their restricting structural characteristics are potential reasons behind their lower technical efficiency. The highly specialized crop-livestock enterprises are, however, medium-sized farms primarily focusing on either cereals or olive cultivations, in addition to other minor secondary activities. Highly specialized farms are faced with many challenges of market access and reliability and are affected by different types of risks compared to other, more diversified farms. These are all possible reasons for the lower technical efficiency of this group of farms. The empirical findings are consistent with other results in which the variability in technical efficiency is correlated across farming systems (Mariano et al., 2011; Rahman et al., 2011; Asante et al., 2020). Results suggest that diversified smallholders under CA farming systems appear to be operating not only at higher technical efficiencies but also translating into higher income (Table 3) toward promoting diversification (Table 4).

## Evidence of synergies and economies of diversification in crop-livestock systems under the CA farming system

The model defined by Equation 8 is used to evaluate to what extent there are complementary synergies between farm activities. Results show evidence of complementary synergies between four of the six output combinations (Table 5). The relative coefficients of the second-order cross-partial derivatives indicate the strength of complementarity between three combinations from these four pairs: cereals with forage crops, cereals with legumes, and forage crops with livestock. The measured parameters for these three combinations are significant at $P < 0.05$. The fourth positive combination of forage crops with legumes is not significant.

The assessment of the crop-livestock combination reveals a high synergy between forage crops and livestock (with a parameter value of 0.56 significant at $P < 0.05$). This result implies that livestock production and forage crops are complementary activities, resulting in higher productivity among smallholder farmers operating under CA farming systems in Tunisian semiarid regions. This is not surprising,

TABLE 5 Empirical coefficients of the cross-products of outputs in the input distance function.

| Variables | Estimates | Standard deviation | *t*-values |
|---|---|---|---|
| Cereals with forage crops | 2.84 | 0.97 | 2.91*** |
| Cereals with legumes | 0.16 | 1.02 | 1.62** |
| Cereals with livestock | 0.13 | 1.01 | 0.13 |
| Forage crops with legumes | −1.01 | 1.01 | −1.00 |
| Forage crops with livestock | 0.56 | 0.97 | 1.57* |
| Legumes with livestock | −2.31 | 0.93 | −2.48*** |

*, **, *** Significant at 10, 5, and 1%, respectively.
Source: own elaboration from model results (2022).

and strong complementarity indicates how this efficient combination is well integrated by diversified farm smallholders. Under CA, integrated crop-livestock systems are a form of sustainable intensification of agriculture that relies on harmonious relationships between forage and animal feeding system elements to reinforce critical agroecosystem processes, with potential impacts on farm-level productivity and resilience to climate change threats.

Similarly, the synergies between cereals (e.g., wheat) and legume crops (which are largely dual-purpose) in the cereal–livestock system indicate the synergetic way the diversified farmers have integrated these crop combinations in CA farming systems. This result reveals the benefit of this synergy toward improving soil health, including increasing soil organic matter, due to the adoption of conservation practices such as CA (Laroca et al., 2018; Souissi et al., 2020). Evidence suggests that crop diversification strategies applied by diversified smallholders under CA, such as combining legumes with wheat production in an efficient agronomic and management way, will provide a beneficial effect in improving soil fertility and, thus, enhancing productivity among all produced crops. The highest significant synergy is between cereals and forage crops (coefficient value of 2.84). The capacity of wheat crop activity to strengthen the complementarity with the forage crop activity is still strong, reflecting the complementarity advantages gained from the traditional small-ruminant (i.e., sheep)-cereal (i.e., wheat/barley) farming system under CA. The evidence of only slight and non-significant synergies between cereals and livestock activity is surprising, given the high levels of labor and farming management skills that both activities could share within the crop-livestock farming system. The existing competition between the two activities for the same inputs (e.g., land and labor) provides evidence of the low level of synergy. Chavas and Di Falco (2012) discussed the existing synergies in crop diversification in Ethiopian crop-farming systems. Similar synergies were also found in several global contexts, such as mixed farms in Australian wheat–sheep farming systems (Villano et al., 2010), Ghana crop-livestock farming systems (Asante et al., 2020), and Brazilian mixed crop-livestock systems (Carvalho et al., 2018; Peterson et al., 2020).

In this research paper, Carvalho et al. (2018) examined cover crop grazing as a management strategy for land-use diversification and sustainable intensification of agriculture in Brazil. The authors suggested that the use of animals to graze cover crops in rotation with cash crops while using no-till farming techniques added a level of system complexity uncommon in current food production systems. In such systems, emergent features result from complex interactions between the soil compartment, plants, and animals, which act as a storehouse of markers of higher-level ecosystem functioning. The management tool in ICLS that influences system performance in terms of positive or negative looping feedback is grazing intensity. A moderate grazing intensity is required to encourage positive feedbacks that balance productivity and sustainability. This has consequences for increased system resilience and economic profitability. Schuster et al. (2018) argued that grazing management and its relationship with crop rotation determine the severity of weed infestation in an ICLS, and the most important element influencing weed outcomes is forage allowance, together with the conventional management of no-tillage ICLS.

Such findings suggest that diversifying output combinations would lead to additional synergies for farm households that branch out into these activities under crop-mixed farming systems.

There are significant and non-complementary synergies between legumes and livestock (coefficient of −2.31). The fact that we found no evidence of significant dis-synergies between these two activities means that smallholder farmers operating under CA would not benefit from more specialized production processes in the landscape context considered in this research study. Legumes cultivated in the study area are usually rainfed food legumes (fava beans, chickpeas, lentils), which are either cultivated in open fields or between the lines of olive trees. As shown in the table, legumes in the study area are also negatively interacting with forage crops, which is indeed the case in the production systems investigated. For a farmer with small to medium livestock breeders, a preferred rotation will be to cultivate forage crops, which are essential to minimizing their feeding production costs. Farmers without livestock tend to cultivate food legumes. This suggests a benefit of diversification under CA farming systems, in which smallholder farmers integrate crops and livestock simultaneously to ensure the sustainability of their farming systems. The t-statistics and magnitude of the coefficient linking forage and legumes suggest a weak and non-significant complementary synergy between these two crops. This could be because legume crop production competes with the production of other crops (e.g., wheat and forage crops) on the limited existing resources, and so enhancing the production of legumes means sacrificing the limited resources to produce forage crops.

From the above, we can argue that the concept of integrated crop-livestock systems under CA has not been adequately adopted by smallholder farmers, and the agricultural system in the studied region continues to exhibit a low level of productivity and resource use efficiency. From another perspective, food insecurity indicators remained high among smallholder farming communities producing crops and livestock despite the availability of arable land, technologies, and an abundance of other natural resources. This suggests the need to better understand and address such complex problems as food security for these communities, as managing such diversified production systems could lead to a positive impact on reducing poverty and improving food security. This evidence was supported by Szymczak et al. (2020) in a study focusing on Brazilian smallholder farmers. They argue that in addition to diversifying the system, combining cropping with livestock was a good way to increase economic resilience. In the same sense, Danso-Abbeam et al. (2021), by applying a network model, investigate the input and output flow in a Latino Caribbean farm's integrated crop-livestock system and its relation to food security. They conclude that, with a significance level of 5%, the integrated crop-livestock diversity index was found to have a positive and significant impact on food security.

## Conclusions and policy implications

This paper provides an empirical evaluation of diversification economies in crop-livestock systems, with a special focus on measuring technical efficiency and assessing complementary synergies at the smallholder farming system level operating under CA farming systems in the Tunisian dryland areas.

The objective of this study was to assess whether diversification or specialization in crop-livestock systems, conducted under CA, can be accredited to the exploration for better economic performance. Examining the economies of diversification under this system helps understand if smallholders can benefit from synergies through cost savings by choosing the optimal combination of outputs in crop-livestock production under a CA farming system. Additionally, this study also examined evidence concerning economies of scale in integrated CL systems among smallholder farmers. A stochastic input distance function was used, and a measure of synergies was undertaken based on an empirical framework of the second-order cross-partial derivative of output variables in the distance function model.

Empirical findings revealed that technical inefficiencies are significant in CL systems, suggesting that enhancing CL diversification will lead to improvements in technical efficiency. The key driving forces that significantly improved technical efficiency were farmers' education level, the share of off-farm income, and access to credit. This finding has important implications because it suggests that actions on these factors would lead to higher technical efficiency in crop-livestock production under CA. This result implies that policies in drylands:

- Consider the improvement in demographic characteristics (e.g., education, extension services, and knowledge of CA technology management) and institutional factors (e.g., *Agricultural Development Group* - GDA, *Mutual Agricultural Service Company* SMSA, and cooperatives).
- Provide financial support (i.e., credits and loans) with low-interest rates to smallholder farmers is considered a good way to overcome some of the financial barriers associated with *technology adoption* by these dryland farmers.
- While extension policy is expected to play an important role in enhancing the diversification and consequently the evolution of agricultural production, specifically crop-livestock production under CA, our findings emphasize the need to use the most effective extension measures. This could be through a participatory method of training including all key actors and at all levels (research, private, and extension) to both improve the access of farmers to various pieces of training and raise their awareness, particularly those who practice agricultural diversification under CA farming systems.
- Design appropriate strategies for enhancing the production of specific output combinations in crop-livestock diversified systems under CA among smallholders in rainfed areas.
- Promote the production and integration of crops such as legumes with other crops and livestock with other crops in diversified farming systems to enhance overall farm productivity. This will reduce food insecurity and poverty among rural farm households and the entire rural population.

These actions will certainly contribute to helping increase farmers' adaptive capacity and their acceptance of the adoption of agricultural diversification practices and ensure they generate concrete benefits by increasing income through sustainable agricultural operations and farming practices.

The contribution of diversification in output combinations to technical efficiency was very high and significant, indicating that specialization in integrated crop-livestock under CA farming systems leads to greater technical inefficiency. The evidence of strong synergies from complementarity between sheep and crop activities (e.g., forage crops) under CA farming systems implies that crop-livestock diversification is a desirable strategy for improving overall farm productivity. However, to achieve this, policymakers should include strategies for enhancing the production of specific output combinations in crop-livestock diversification systems among smallholders in Tunisia's arid areas. Such policies should promote the production and integration of crops such as wheat with forage crops and livestock with crop forages in diversified farming systems to enhance overall farm productivity.

The empirical findings presented in this paper were an attempt to help assess and understand the role that agricultural diversification can play in improving the livelihoods of CL farming households by generating high levels of income, especially under CA farming systems. By incorporating input distance functions into the productivity-based approach used in this research we were also able to assess the economic benefits of diversification to comprehend the economics of CL diversification.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

Conceptualization, validation, and writing—review and editing: BD, AFo, AFr, MA, HM'h, HO, and MR. Formal analysis: BD, AFo, AFr, MA, and HO. Investigation: BD, AFo, AFr, MA, HM'h, and MR. Software: BD, AFo, AFr, and MA. Writing—original draft: BD, AFo, AFr, MA, and HM'h. All authors contributed to manuscript revision, read, and approved the submitted version.

## Funding

This research was conducted as part of the "Use of Conservation Agriculture in Crop–Livestock Systems (CLCA) in the Drylands for Enhanced Water Use Efficiency, Soil Fertility and Productivity in NEN and LAC Countries" project (https://mel.cgiar.org/projects/clca2) funded by IFAD (https://www.ifad.org/en/), under a grant agreement with the International Center for Agricultural Research in the Dry Areas (ICARDA—http://www.icarda.org – Agreement #20016) within the framework of the CGIAR Research Program on Livestock (https://livestock.cgiar.org/). This research was also partially funded by the CGIAR Research Initiative on Transformational Agroecology Across Food, Land, and Water Systems (Agreement #200302).

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## Author disclaimer

The opinions expressed here belong to the authors and do not necessarily reflect those of ICARDA, CGIAR, or IFAD.

## References

Abdulai, A., and Abdulai, A. (2017). Examining the impact of conservation agriculture on environmental efficiency among maize farmers in Zambia. *Environ. Dev. Econ.* 22, 177–201. doi: 10.1017/S1355770X16000309

Ameur, W., Frija, A., Abdeladhim, M.A., and Thabet, C. (2021). Patterns of use of residue biomass in cereal–sheep production systems of North Africa: case of Tunisia. *Agronomy.* 11, 1–18. doi: 10.3390/agriculture11070612

Angar, H. (2010). *Le développement de l'agriculture de conservation en Tunisie: Séminaire National: Dix ans d'Agriculture de Conservation en Tunisie: Bilan et Perspectives.* Institut national des grandes cultures (INGC) - Tunisie.

Asante, B. O., Villano, R. A., and Battese, G. E. (2020). Evaluating complementary synergies in integrated crop-livestock systems in Ghana. *Int. J. Soc. Econ.* 47, 72–85. doi: 10.1108/IJSE-04-2019-0274

Asante, B. O., Villano, R. A., Patrick, I. W., and Battese, G. E. (2018). Determinants of farm diversification in integrated crop–livestock farming systems in Ghana. *Renew. Agric. Food. Syst.* 33, 131–149. doi: 10.1017/S1742170516000545

Asefa, S. (2011). *Analysis of technical efficiency of crop producing smallholder farmers in Tigray, Ethiopia.* Available online at: https://mpra.ub.uni-muenchen.de/40461/ (accessed December 2021).

Baccouri, S. (2008). *Conservation Agriculture in Tunisia. Conservation Ag. Carbon Offset Consultation.* West Lafayette/USA: FAO-CTIC.

Bachta, M. S. (2011). La céréaliculture en Tunisie Une politique de régulation à repenser. *Les notes d'analyse du CIHEAM.* 64, 19.

Bahri, H., Annabi, M., Cheikh M'hamed, H., Chibani, R., Chtourou, M., Riahi, N., et al. (2018). Evaluation de l'impact agro-environnemental et de la durabilité de l'adoption du semis direct au Nord de la Tunisie. *Ann INRAT.* 91, 98–111.

Bahri, H., Annabi, M., Cheikh M'hamed, H., and Frija, A. (2019). Assessing the long-term impact of conservation agriculture on wheat-based systems in Tunisia using APSIM simulations under a climate change context. *Sci.Tot.Env.* 1223–1233. doi: 10.1016/j.scitotenv.2019.07.307

Banker, R. D., Zheng, Z. E., and Natarajan, R. (2010). DEA-based hypothesis tests for comparing two groups of decision-making units. *Eur. J. Oper. Res.* 206, 231–238. doi: 10.1016/j.ejor.2010.01.027

Battese, G. E., and Coelli, T. J. (1995). A model for technical inefficiency effects in a stochastic frontier production function for panel data. *Empir. Econ.* 20, 325–332. doi: 10.1007/BF01205442

Baumol, W. (1982). Contestable markets: an uprising in the theory of industry structure. *Am. Econ. Rev.* 72, 1–15. doi: 10.2307/134928

Byrnes, R. C., Eastburn, D. J., Tate, K. W., and Roche, L. M. (2018). A global meta-analysis of grazing impacts on soil health indicators. *J. Environ. Qual.* 47, 758–765. doi: 10.2134/jeq2017.08.0313

Carvalho, P. C., de, F., Peterson, C. A., Nunes, P. A. de, A., Martins, A. P., de Souza Filho, W., et al. (2018). Animal production and soil characteristics from integrated crop-livestock systems: toward sustainable intensification. *J.Ani.Sci.* 96, 3513–3525. doi: 10.1093/jas/sky085

Chaplin, H. (2000). *Agricultural diversification: a review of methodological approaches and empirical evidence.* Available online at: http://www.ilr.uni-bonn.de/agpo/rsrch/Idara/Farm/wyewp2.doc (accessed December 2021).

Chavas, J. P., and Aliber, M. (1993). An analysis of economic efficiency in agriculture: a nonparametric approach. *J. Agric. Resour. Econ.* 18, 1–16.

Chavas, J. P., and Di Falco, S. (2012). On the role of risk vs. economies of scope in farm diversification with an application to Ethiopian farms. *J. Agric. Econ.* 63, 25–55. doi: 10.1111/j.1477-9552.2011.00319.x

Chavas, J. P., and Kim, K. (2007). Measurement and sources of economies of scope: a primal approach. *J. Inst. Theor. Econ.* 163, 411–427. doi: 10.1628/093245607781871354

Chavas, J. P., and Kim, K. (2010). Economies of diversification: a generalization and decomposition of economies of scope. *Int. J. Prod. Econ.* 26, 229–235. doi: 10.1016/j.ijpe.2010.03.010

Cheikh M'hamed, H., Bahri, H., and Annabi, M. (2018). *Conservation agriculture in Tunisia: historical, current status and future perspectives for rapid adoption by smallholder farmers.* Johannesburg, South Africa: Second African Congress on Conservation Agriculture. p. 57–60.

Cheikh M'hamed, H., Bahri, H., Annabi, M., Frija, A., and Idoudi, Z. (2022). "Historical Review and Future Opportunities for Wider Scaling of Conservation Agriculture in Tunisia," *Conservation agriculture in Africa: climate smart agricultural development*, Mkomwa, S., Kassam, A., (ed.). p. 475. doi: 10.1079/9781789245745.0007

Coelli, T. J., and Fleming, E. (2004). Diversification economies and specialisation efficiencies in a mixed food and coffee smallholder farming system in Papua New Guinea. *Agric. Econ.* 31, 229–239. doi: 10.1111/j.1574-0862.2004.tb00260.x

Coelli, T. J., and Perelman, S. (2000). Technical efficiency of European railways: a distance function approach. *Appl. Econ.* 32, 1967–1976. doi: 10.1080/00036840050155896

Danso-Abbeam, G., Dagunga, G., Ehiakpor, D. S., Ogundeji, A. A., Setsoafia, E. D., and Awuni, J. A. (2021). Crop–livestock diversification in the mixed farming systems: implication on food security in Northern Ghana. *Agri. Food Secur.* 10, 1–14. doi: 10.1186/s40066-021-00319-4

DGACTA. (2017). Direction Générale de l'Aménagement et de la Conservation des Terres Agricoles: *Elaboration de la Stratégie de Conservation des Eaux et des Sols de la Tunisie*, Ministère de l'Agriculture, des Ressources Hydrauliques et de la Pèche, Tunisie, p. 202.

FAO (2010). *An international consultation on integrated crop-livestock systems for development: The way forward for sustainable production intensification.* Rome: Integrated Crop Management. Available online at: https://www.fao.org/publications/card/en/c/1ffb177e-64c9-5e77-8614-1342b8643e9d/

Frelat, R., Lopez-Ridaura, S., Giller, K. E., Herrero, M., Douxchamps, S., Djurfeldt, A. A., et al. (2016). Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proc. Natl. Acad. Sci. U.S.A.* 113, 458–463. doi: 10.1073/pnas.1518384112

Friedrich, T., Derpsch, R., and Kassam, A. (2012). Overview of the global spread of conservation agriculture. *Field Actions Sci. Rep. 6, 9.*

Guesmi, H., Salem, H., and Moujahed, N. (2019). Integration crop-livestock under conservation agriculture system. *J. New. Sci.* 65, 4061–4065.

Hadley, D. (2006). Patterns in technical efficiency and technical change at the farm-level in England and Wales, 1982–2002. *J. Agric. Econ.* 57, 81–100. doi: 10.1111/j.1477-9552.2006.00033.x

Ibrahim, H., Rahman, S., Envulus, E., and Oyewole, S. (2009). Income and crop diversification among farming households in a rural area of north central Nigeria. *Agro. Sci.* 8, 84–89. doi: 10.4314/as.v8i2.51102

IFAD (2010). *Integrated Crop–Livestock Farming Systems. Livestock Thematic Papers. Tools for Project Design.* Rome: IFAD

Joshi, P. K., Gulati, A., Birthal, P. S., and Tewari, L. (2004). Agriculture diversification in South Asia: patterns, determinants and policy implications. *Econ. Polit. Wkly.* 39, 2457–2467.

Joshi, P. K., Gulati, A., and Cummings, R. W. (2007). *Agricultural Diversification and Smallholders in South Asia.* New Delhi, India: Academic Foundation.

Joshi, P. K., Joshi, L., and Birthal, P. S. (2006). Diversification and its impact on small holders: Evidence from a study on vegetable production. *Agric. Econ.* 19, 219–236.

Kankwamba, H., Mapila, M., and Pauw, K. (2012). *Determinants and Spatio-Temporal Dimensions of Crop Diversification in Malawi. Project Report – No 2.* Malawi: IFPRI.

Karimov, A. A. (2014). Factors affecting efficiency of cotton producers in rural Khorezm, Uzbekistan: Re-examining the role of knowledge indicators in technical efficiency improvement. *Agric. Econ.* 2, 1–16. doi: 10.1186/s40100-014-0007-0

Kassam, A., Kueneman, E., Kebe, B., Ouedraogo, S., and Youdeowei, A. (2009). *Enhancing crop-livestock systems in conservation agriculture for sustainable production intensification: a farmer discovery process going to scale in Burkina.* Integrated Crop Management. Rome: FAO.

Kassam, A. H., Friedrich, T., Shaxson, F., and Pretty, J. (2009). The spread of conservation agriculture: justification, sustainability and uptake. *Int. J. Agric. Sust.* 7, 292–320 doi: 10.3763/ijas.2009.0477

Khaldi, R., and Saaidia, B. (2017). *Analyse de la Filière Céréalière en Tunisie et Identification des Principaux Points de Dysfonctionnement à L'origine des Pertes.* Rapport de projet FAO (GCP/RNE/004/ITA). p. 102. Available online at: http://www.onagri.nat.tn/uploads/Etudes/RapportIVF.pdf (accessed November 2022).

Klapwijk, C. J., van Wijk, M. T., Rosenstock, T. S., van Asten, P. J. A., Thornton, P. K., and Giller, K. E. (2014). Analysis of trade-offs in agricultural systems: current status and way forward. *Cur Opi Env Sust.* 6, 110–115. doi: 10.1016/j.cosust.2013.11.012

Komarek, A. M., Kwon, H., Haile, B., Thierfelder, C., Mutenje, M. J., and Azzarri, C. (2019). From plot to scale: ex-ante assessment of conservation agriculture in Zambia. *Agric. Syst.* 173, 504–518. doi: 10.1016/j.agsy.2019.04.001

Landers, J. N. (2007). *Tropical Crop-Livestock Systems in Conservation Agriculture: The Brazilian Experience.* Rome: FAO: Integrated Crop Management.

Laroca, J. V., dos, S., Souza, J. M. A. de, Pires, G. C., Pires, G. J. C., Pacheco, L. P., Silva, F. D., et al. (2018). Soil quality and soybean productivity in crop-livestock integrated system in no-tillage. *Pesquisa Agropecuária Brasileira* 53, 1248–1258. doi: 10.1590/s0100-204x2018001100007

Latruffe, L., Balcombe, K., Davidova, S., and Zawalinska, K. (2004). Determinants of technical efficiency of crop and livestock farms in Poland. *Appl. Econ.* 36, 1255–1263 doi: 10.1080/0003684042000176793

Liniger, H., Mekdaschi, S. R., Hauert, C., and Gurtner, M. (2011). *Sustainable Land Management in Practice: Guidelines and Best Practices for Sub-Saharan Africa: Field Application.* Rome: FAO

Loreau, M. (1998). Biodiversity and ecosystem functioning: a mechanistic model. *Proc. Natl. Acad. Sci. U. S. A.* 95, 5632–5636. doi: 10.1073/pnas.95.10.5632

Mariano, M. J., Villano, R., and Fleming, E. (2011). Technical efficiency of rice farms in different agroclimatic zones in the Philippines: an application of a stochastic metafrontier model. *Asian. Econ. J.* 25, 245–269. doi: 10.1111/j.1467-8381.2011.02060.x

Martin, G., Moraine, M., Ryschawy, J., Magne, M. A., Asai, M., Sarthou, J. P., et al. (2016). Crop–livestock integration beyond the farm level: a review. *Agron. Sustain. Dev.* 36, 1–21. doi: 10.1007/s13593-016-0390-x

Marzin, J., Bonnet, P., Bessaoud, O., and Ton-Nu, C. (2017). *Study on Small-Scale Family Farming in the Near-East and North Africa Region: Synthesis.* Rome: FAO

Masmoudi, A. (2012). *Etude de certains paramètres de durabilité des systèmes de production céréaliculture-élevage dans le contexte de l'intégration des techniques de l'agriculture de conservation. [Doctoral dissertation].* Sétif: Université de Sétif 1-Ferhat Abbas

Mesfin, W., Fufa, B., and Haji, J. (2011). Pattern, trend and determinants of crop diversification: Empirical evidence from smallholders in Eastern Ethiopia. *J. Econ. Sust. Dev.* 2, 78–89.

Mhazo, N., Manyatsi, A. M., Masarirambi, M. T., and Mhazo, M. L. (2010). Conservation agriculture in an integrated crop and livestock farming system Challenges and opportunities in Swaziland. Swaziland. *J. Sust. Dev.* 1, 1–69.

Moraine, M., Duru, M., Nicholas, P., Leterme, P., and Therond, O. (2014). Farming system design for innovative crop–livestock integration in Europe. *Animal* 8, 1204–1217. doi: 10.1017/S1751731114001189

Moujahed, N., Abidi, S., Youssef, S. B., Darej, C., Chakroun, M., and Salem, H. B. (2015). Effect of stocking rate on biomass variation and lamb performances for barley stubble in Tunisian semi arid region and under conservation agriculture conditions. *African J. Agric. Res.* 10, 4584–4590. doi: 10.5897/AJAR2015.10396

Mrabet, R., Bahri, H., Zaghouane, O., Cheikh M'Hamed, H., Mohamed El-Areed, S.-R., and Abou El-Enin, M.-M. (2022). "Adoption and spread of Conservation

Agriculture in North Africa," in *Advances in Conservation Agriculture Volume 3* Kassam, A. (ed.). Cambridge, UK: Adoption and Spread, Burleigh Dodds Science Publishing. p. 185–230 doi: 10.19103/AS.2021.0088.06

Ogundari, K. (2013). Crop diversification and technical efficiency in food crop production: a study of peasant farmers in Nigeria. *Int. J. Soc. Econ*. 40, 267–287 doi: 10.1108/03068291311291536

Paul, C. J. M., and Nehring, R. (2005). Product diversification, production systems, and economic performance in US agricultural production. *J. Econ*. 126, 525–548 doi: 10.1016/j.jeconom.2004.05.012

Peterson, C. A., Bell, L. W., Carvalho, P. C. D. F., and Gaudin, A. C. (2020). Resilience of an integrated crop–livestock system to climate change: a simulation analysis of cover crop grazing in southern Brazil. *Front. Sust. Food Syst.* 4, 604099 doi: 10.3389/fsufs.2020.604099

Petit, M., and Barghouti, S. (1992). "Diversification: challenges and opportunities," in *Trends in Agricultural Diversification,* Barghouti, S., Garbus, L., and Umali, D. (Washington DC: World Bank) p. 1–13.

Pope, R. D., and Prescott, R. (1980). Diversification in relation to farm size and other socioeconomic characteristics. *Am. J. Agric. Econ*. 62, 554–559. doi: 10.2307/1240214

Rahman, S. (2009). Whether crop diversification is a desired strategy for agricultural growth in Bangladesh? *Food Policy.* 34, 340–349. doi: 10.1016/j.foodpol.2009.02.004

Rahman, S., Barmon, B. K., and Ahmed, N. (2011). Diversification economies and efficiencies in a 'BlueGreen Revolution' combination: a case study of prawn-carp-rice farming in the 'Gher' system in Bangladesh. *Aquac. Int.* 19, 665–682. doi: 10.1007/s10499-010-9382-z

Raunet, M., Richard, J. F., and Rojat, D. (2004). Premiers résultats d'introduction du semis direct sous couvert et lutte antiérosive en Tunisie, in *Gestion de la biomasse, érosion et séquestration du carbone. Séquestration du carbone et érosion des sols,* Roose, E., De Noni, G., Prat, C., Ganry, F. and Bourgeon, G. (Eds). Paris, France: institut de recherche pour le développement. p. 388–404.

Rekik, M., Frija, A., Idoudi, Z., López Ridaura, S., Louahdi, N., Dhehibi, B., et al. (2021). *Use of Conservation Agriculture in Crop-Livestock Systems (CLCA) in the Drylands for Enhanced Water Use Efficiency, Soil Fertility and Productivity in NEN and LAC Countries – Progress Highlights: Year (3) - April 2020 to March 2021*. Lebanon: International Center for Agricultural Research in the Dry Areas (ICARDA).

Richard, F. (2005). *Le semis direct en Tunisie, La, Gazette des SCV au Cirad*. Groupe Agence Française de Développement (AFD-France), 68 p. Available online at: http://open-library.cirad.fr/files/2/230__1162774426.pdf

Ryan, J. G., and Spencer, D. (2001). *Future Challenges and Opportunities for Agricultural RandD in the Semi-arid Tropics*. Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics.

Schuster, M. Z., Harrison, S. K., de Moraes, A., Sulc, R. M., Carvalho, P. C. F., Lang, C. R., et al. (2018). Effects of crop rotation and sheep grazing management on the seedbank and emerged weed flora under a no-tillage integrated crop-livestock system. *J. Agri. Sci.* 1–11. doi: 10.1017/S0021859618000813

Shephard, R. W. (1953). *Cost and Production Functions*. Princeton: Princeton University Press.

Sichoongwe, K., Mapemba, L., Ng'ong'ola, D., and Tembo, G. (2014). *The Determinants and Extent of Crop Diversification Among Smallholder Farmers: A Case Study of Southern Province, Zambia*. Washington, DC: IFPRI. doi: 10.5539/jas.v6n11p150

Singbo, A. G., Emvalomatis, G., and Oude Lansink, A. (2021). The effect of crop specialization on farms' performance: a Bayesian non-neutral stochastic frontier approach. *Front. Sustain. Food Syst.* 5, 711530. doi: 10.3389/fsufs.2021.711530

Souissi, A., Bahri, H., Cheikh M'hamed, H., Chakroun, M., Ben Youssef, S., Frija, A., et al. (2020). Effect of Tillage, Previous Crop, and N Fertilization on Agronomic and Economic Performances of Durum Wheat (Triticum durum) under Rainfed Semi-arid Environment. *Agronomy*. 10, 1–16. doi: 10.3390/agronomy10081161

Szymczak, L. S., de Faccio, P., Lurette, C. A., De Moraes, A., de Albuquerque Nunes, P. A., et al. (2020). *System Diversification and Grazing Management as Resilience-Enhancing Agricultural Practices: The Case of Crop-Livestock Integration*. Agricultural Systems, Elsevier Masson. p. 184.

Tarawali, S., Keating, J., Powell, J., Hiernaux, P., Lyasse, O., and Sanginga, N. (2004). "Integrated natural resource management in West African crop–livestock systems," in *Sustainable Crop–livestock Production for Improved Livelihoods and Natural Resource Management in West Africa*, Williams, T. P., Tarawali, S. A., Hiernaux, P., and Fernandez-Rivera, S. (Ibadan: IITA) p. 349–370.

Theodoridis, A., Ragkos, A., Roustemis, D., Arsenos, G., Abas, Z., and Sinapis, E. (2014). Technical indicators of economic performance in dairy sheep farming. *Animal.* 8, 133–140. doi: 10.1017/S1751731113001845

Tibesigwa, B., Visser, M., and Turpie, J. (2015). The impact of climate change on net revenue and food adequacy of subsistence farming households in South Africa. *Environ. Dev. Econ*. 20, 327–353. doi: 10.1017/S1355770X14000540

Tilman, D., Wedin, D., and Knops, J. (1996). Productivity and sustainability influenced by biodiversity in grassland ecosystems. *Nature.* 379, 718–720 doi: 10.1038/379718a0

Tittonell, P., Gérard, B., and Erenstein, O. (2015). Tradeoffs around crop residue biomass in smallholder crop-livestock systems – What's next?, *Agr Sys*. 134, 119-128. doi: 10.1016/j.agsy.2015.02.003

Villano, R., Fleming, E., and Fleming, P. (2010). Evidence of farm-level synergies in mixed-farming systems in the Australian wheat-sheep zone. *Agric. Syst.* 103, 146–152. doi: 10.1016/j.agsy.2009.11.005

Vyas, V. (2006). "Diversification in agriculture: concept, rationale and approaches," in *Indian Agriculture in the New Millennium: Changing Perceptions and Development Policy,* Mujumdar, N. A., and Kapila, U. (New Delhi: Academic Foundation) p. 245–256.

Weiss, C. R., and Briglauer, W. (2000). *Determinants and Dynamics of Farm Diversification. FE Working Paper-No. 2.* Kiel: Universität Kiel, Department of Food Economics and Consumption Studies.

Yachi, S., and Loreau, M. (2007). Does complementary resource use enhance ecosystem functioning? A model of light competition in plant communities. *Ecol. Lett*. 10, 54–62. doi: 10.1111/j.1461-0248.2006.00994.x

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 09 January 2023
DOI 10.3389/fsufs.2022.1016404

OPEN ACCESS

EDITED BY
Sendhil R.,
Pondicherry University, India

REVIEWED BY
Suresh Kurup,
Central Institute of Fisheries
Technology (ICAR), India
Shokhrukh-Mirzo Jalilov,
Commonwealth Scientific and
Industrial Research Organisation
(CSIRO), Australia

*CORRESPONDENCE
Sreedhar Upendram
✉ supendra@utk.edu

SPECIALTY SECTION
This article was submitted to
Land, Livelihoods and Food Security,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 10 August 2022
ACCEPTED 16 December 2022
PUBLISHED 09 January 2023

CITATION
Upendram S, Regmi HP, Cho S-H,
Mingie JC and Clark CD (2023) Factors
affecting adoption intensity of climate
change adaptation practices: A case of
smallholder rice producers in Chitwan,
Nepal.
*Front. Sustain. Food Syst.* 6:1016404.
doi: 10.3389/fsufs.2022.1016404

# Factors affecting adoption intensity of climate change adaptation practices: A case of smallholder rice producers in Chitwan, Nepal

Sreedhar Upendram[1]*, Hari P. Regmi[2], Seong-Hoon Cho[1], James C. Mingie[1] and Christopher D. Clark[1]

[1]Department of Agricultural and Resource Economics, The University of Tennessee Institute of Agriculture, Knoxville, TN, United States, [2]Department of Agricultural Economics, Purdue University, West Lafayette, IN, United States

This study examines how smallholder rice producers' adoption intensity for climate change adaptation practices (i.e., improved varieties, irrigation practices, direct seeded rice, integrated pest management, and adjustment in crop calendar) is influenced by access to Extension services, training, weather-related information, and membership in farmer groups or cooperatives (referred to as "institutional resources"). We use survey data collected from 359 smallholder rice producers in the Chitwan district of Nepal in 2019. The results indicate that: (1) access to institutional resources significantly enhance the likelihood of adoption of more climate change adaptation practices; (2) high intensity climate change adaptation practice measured by the adoption of three, four, and five practices significantly increases with access to institutional resources; (3) intensity of adoption of climate change adaptation practices is reduced with greater adaptation alternatives available to rice producers; and (4) lack of information and technical knowledge are the most important reasons for non-adoption of climate change adaptation practices by smallholder rice producers. The results are valuable for policy makers and planners to prioritize training opportunities and allocate scarce resources to enhance climate change adaptation and improve sustainability of rice production practices.

KEYWORDS

**climate change, small land holders, adaptation, non-adoption, Nepal, intensity**

## Introduction

Climate change is one of the greatest challenges of the 21st century, threatening human nutrition, health, and development. Climate extremes continue to adversely affect agricultural productivity and food security in many regions around the world (IPCC, 2019). Smallholder producers in developing countries rely heavily on subsistence agriculture and their livelihoods are particularly vulnerable to climate change (Wheeler and Von Braun, 2013; Bandara and Cai, 2014; Harvey et al., 2014; Sarker et al., 2014). The impacts of climate change on agriculture vary substantially and are dependent on risk mitigation measures that improve the resilience of systems and promote sustainable development (Smit and Wandel, 2006; Morton, 2007; Aryal et al., 2020).

As the benefits of climate change adaptation to farmers have been well established (Teklewold et al., 2013; Aryal et al., 2020), a branch of literature has emerged on methods to encourage smallholder producers to adopt climate change adaptation practices in developing countries (Morton, 2007; Kurukulasuriya and Rosenthal, 2013). The literature using case studies find that: (1) understanding producer behavior is important to design effective climate change adaptation practices and improve overall sustainability of agricultural production (Feola et al., 2015); (2) climate risk perception and psychological elements influence smallholder producers' adaptation behavior (Azadi et al., 2019); and (3) access to institutional resources such as Extension services, skill enhancement training, location specific adaptation options, climate and weather information, membership in co-operatives in addition to education, support services and lines of credits have a positive effect on producer attitudes toward climate change adaptation (Bryan et al., 2009; Deressa et al., 2009; Gbetibouo, 2009; Tazeze et al., 2012; Piya et al., 2013; Mulwa et al., 2017; Zamasiya et al., 2017; Aryal et al., 2018; Khanal et al., 2018).

The different level of role of the access to institutional resources on climate change adaptation is a key takeaway from the existing literature as the information has clear implications for smallholder producers in developing countries. Despite the contributions of many studies on climate change adaptations in developing countries, a major gap in literature is that most of the studies have only examined the effect of the access to institutional resources with a single climate change adaptation practice at a time. Adjusting planting dates to coincide with monsoon onset, use of drought tolerant varieties and late harvest to mitigate impacts of monsoon are a few ways in which smallholder rice producers adapt to climate change. In practice, a producer in each crop season has the choice of adopting multiple climate change adaptation practices at the same time. For example, climate change adaptation practices include planting drought-tolerant, short-duration, disease-resistant varieties (referred to as "improved varieties"), practicing soil and water conservation measures, adjusting planting dates due to delayed monsoon, adopting enhanced irrigation practices, and diversifying crops (Deressa et al., 2009; Gbetibouo, 2009; Tazeze et al., 2012; Tilahun and Bedemo, 2014; Gadédjisso-Tossou, 2015; Thinda et al., 2020;). Despite this practical consideration, studies addressing multiple dimensions of climate change adaptation are absent from the literature.

The objective of this research is to determine the role of the access to institutional resources on smallholder rice producer decision-making to adopt multiple climate change adaptation practices. As a case study, we develop an empirical model to estimate the effect of access to institutional resources on adoption intensity of multiple climate change adaptation practices by rice farmers in Chitwan, Nepal (see Figure 1). We focus on how access to four types of institutional resources (i.e., membership in farmers' group and cooperatives, Extension services, training related to farming practices, and weather-related information) affect adoption intensity of five of climate change adaptation practices [i.e., planting improved varieties, adopting enhanced irrigation practices, direct seeded rice (DSR), integrated pest management (IPM), and adjusting planting due to monsoon].

Quantifying the effect of institutional resources on the intensity of climate change adaption enables a decision maker to prioritize farm practices. Understanding the effects on climate change adoption can help streamline resource allocation for institutional resources. Under this premise, if, for example, improving accessibility to one institutional resource is superior to another in increasing the adoption intensity of multiple climate change adaptation practices, financial incentives can improve adoptability of practices.

# Materials and methods

## Study area

Chitwan district of central Nepal was deliberately chosen as a case study because it is a prominent rice-producing district (Figure 1) with smallholder producers experiencing the adverse impacts of climate change on their farming practices (Gurung and Bhandari, 2009). The average farm size is 0.46 hectares (1.13 acres) in Chitwan district. Specifically, climate change adversely impacted rice farming in the plains (*terai* region) of Nepal in terms of acreage, production, and yield (Gumma et al., 2011; Karna, 2014; Khanal et al., 2018). According to Karna (2014), if the day-time maximum temperature surpasses 29.9°C, rice yields start to decline. Gumma et al. (2011) in their study found that variability in the rainfall pattern resulted in 13% reduction in rice acreage in 2006.

Agriculture constitutes one-third of Nepal's gross domestic product and rice is the most cultivated crop of the country (>50% of total cultivated area) (MoAD, 2015; MOF, 2018). In Nepal, only 18% of total cultivable land is under irrigation throughout the year, and nearly 46% of land under cultivation is primarily dependent on monsoon (natural rainfall) for irrigation, potentially leading to high vulnerability to climate change (Ministry of Energy, Water Resources, and Irrigation, 2018; MOF, 2018). Furthermore, the country's rice yield is <4 metric tons/hectare, much lower than the rice yield of other major rice-producing countries (7–8 tons/hectare) (FAO, 2020; National Planning Commission, 2020).

The study area may experience temperature fluctuations and greater variability in precipitation patterns in the future. McSweeney et al. (2010) projects Nepal's temperature to increase

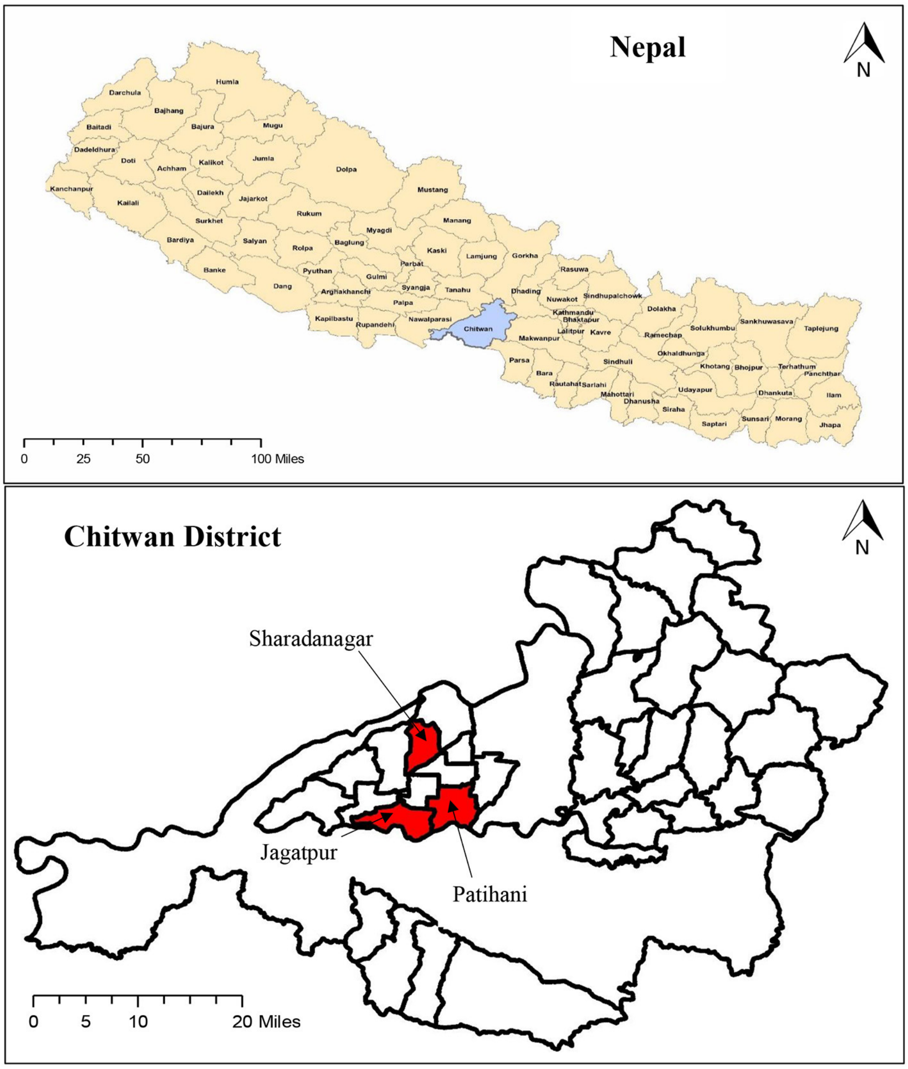


FIGURE 1
Map of Nepal showing Chitwan district and three villages in Chitwan district.

by $1.8^{0}$C by 2030 and $2.8^{0}$C by 2060, and the FAO (2014) projects more intense rainfall events during the rainy season but an overall rainfall decline in the range of 20 mm to 100 mm by 2050. Long-term variation in climatic parameters (primarily rainfall and temperature) and frequent occurrence of extreme weather events such as droughts and floods affect soil-water-plant relationships and results in reduced crop yields (Karna, 2014). Rainfall variability, longer periods of drought, late onset of monsoon, and increasing temperatures have increased the vulnerability of the monsoon-dependent rice production system in Nepal (Karna, 2014; MOF, 2014). Spatial and temporal distribution of rainfall has a noteworthy influence on rice acreage in Nepal. Between 2013 and 2014, rainfall variability adversely affected more than 50,000 hectares of rice and about 127,000 hectares of agricultural land was affected by natural disasters from 2017 to 2018 (MOF, 2014, 2018). Under projected climate change scenarios, rice yields may decline further unless considerable mitigation efforts target address adverse climate change impacts.

## Survey design

Out of the seven administrative units in Chitwan district, the largest administrative unit–*Bharatpur* was deliberately selected. In consultation with the district agricultural Extension office (Chhetri, 2019; Agricultural Knowledge Center, Chitwan), we implemented the survey in three villages where rice is primarily cultivated–*Patihani, Jagatpur and Sharadanagar* (Figure 1). Survey data were collected using a random sampling technique at the household level within the three villages. To collect relevant information on climate change adaptation and rice production, we conducted on-site surveys by interviewing farming households at their respective households, farms, and local gathering spots in the three villages in June 2019. Sample size was determined following Krejcie and Morgan (1970) sample size determination:

$$\text{Sample size} = \frac{\chi^2 \text{NP}\ (1-\text{P})}{\text{d}^2\ (\text{N}-1)+\chi^2 \text{P}\,(1-\text{P})} \tag{1}$$

Where,

$\chi^2$ = Chi-square tabulated value at desired confidence level (95%),
$N$ = Total population size (number of households),
$P$ = Population proportion (assumed to be 0.5),
$d$ = Degree of accuracy expressed as a proportion (0.05).

Following Krejcie and Morgan (1970) a sample of 352 out of a total of 4,090 farming households (N) was determined to be representative to produce parameter estimates at a 95% confidence interval. Out of 383 farming households contacted, 359 (or 94%) agreed to participate in the survey while 24 (or 6.3%) declined to participate in the survey. We trained four enumerators (undergraduate students at Agriculture and Forestry University in Chitwan) to complete the questionnaire with adults in the farming households, and each respondent read a consent statement following Institutional Review Board guidelines about participant involvement, privacy protection and ensuring confidentiality of responses. Upon receiving consent that the participant understood the information and agreed to participate, enumerators asked questions in a face-to-face interaction that lasted approximately 15 min. Within the village, households were selected randomly to participate in the survey. The survey was composed of the following five sections: (1) farm household characteristics; (2) producer perceptions of climate change and variability; (3) adaptation to climate change; (4) producer risk attitudes; and (5) usage status of institutional resources (see Supplementary material for the survey).

We examined five climate change adaptation practices: use of varieties, irrigation, DSR, IPM, and planting adjustment based on a recent National Adaptation Program of Action (NAPA) report (MoE, 2010). NAPA was implemented by the government of Nepal in 2010 to reduce the impacts of climate change. Since agriculture is one of the prioritized sectors in NAPA, many adaptation practices in the agricultural sector such as selection of drought-tolerant and short-duration varieties, investment in improved irrigation, use of local plant extract and bio-pesticides for pest management were detailed in the program (MoE, 2010). Numerous studies indicated that selection of crop varieties, investment in water harvesting and improved irrigation practices, adjustment of crop planting dates, integrated pest management, and crop diversification are important adaptation practices to adapt to climate change and variability (Manandhar et al., 2011; Biggs et al., 2013; Piya et al., 2013). A study by Khanal et al. (2018) reported the use of varieties, improved irrigation, direct seeded rice, fertilizer management, and adjustment of timing of farm operations are all major adaptation practices adopted by rice producers in Nepal.

## Institutional resources

The four institutional resources play a vital role in adaptation to climate change in rice production, and imparting skills among small-holder rice producers to enhance adaptation at the local level as described below:

- Membership in Farmer's Cooperatives or Groups: Producers who are members of cooperatives or groups are better equipped in learning from each other in adapting to climate change. The purpose of a cooperative is to help producers share best farm management practices, obtain needed farm products and services, improve income opportunities, reduce input costs, and manage risk (Aza, 2021). A cooperative also provides a supportive network for producers to discuss challenges and learn from each other in adopting climate change adaptation techniques.
- Extension: Extension agents conduct farm visits and host producers in their offices to answer queries on agricultural problems and challenges. Specifically, Extension agents provide technical expertise and provide information to producers on topics including improved farm management practices, climate change adaptation techniques, newer technologies, and plant protection measures (Regmi et al., 2022). By organizing field days, agricultural fairs, farm visits Extension agents disseminate technical information to motivate producers to adopt improved farming practices. Producers are more likely to contact Extension agents and vice versa if the district office is not very distant and easily accessible. A typical timeframe for a farm visit or an Extension office visit is one day (Singh, 1997).
- Training: Government and non-governmental agencies provide trainings on climate change adaptation to help producers identify, adapt, and mitigate the negative impacts on production practices and profitability (Regmi et al., 2022). The purpose of the trainings is to use latest technology and practices, efficient use of local resources and best management practices. Producers are encouraged to attend these 2–3-day trainings, in-service workshops, or field demonstrations at a central location. At times, trainers provide producers a scholarship or stipend to compensate for their time away from farm and encourage participation in these trainings (Singh, 1997).

TABLE 1 Producers' perceptions of climate change in Chitwan district in the past 10 years (2009–2018).

| Climate change perceptions | % of respondents who perceived climate change in the past 10 years (2009–2018) |
|---|---|
| Weather unpredictability | 99.6% |
| Hailstorms | 97.8% |
| High summer temperature | 86.9% |
| Late onset of monsoon rain | 86.2% |
| Intensity of rainfall | 80.8% |
| Overall change in climate patterns | 76.6% |
| Dry spells | 71.4% |
| High winter temperature | 61.9% |
| Floods | 29.1% |

Source: Regmi, 2020.

- Information: A mass-contact method to quickly disseminate timely information to producers is through factsheets, publications, brochures, booklets, progress reports, Television/radio agricultural progress, weather forecasts, extreme weather events and weather advisories (Regmi et al., 2022). Access to print and digital media are dependent on the literacy of producers and ability to access programs through print, Television, radio, or internet. Many Extension publications are typically available for producers to access at Extension offices (Singh, 1997).

## Producers' perceptions of climate change and variability

In the survey, information about producers perceptions were gathered on local weather patterns over the past 10 years. Specifically, we collected data on changes in temperatures, rainfall, dry periods, floods, hailstorms, unpredictability of weather, groundwater table and onset as well as retreat of monsoon. Climate change is a long-term phenomenon and researchers use long-term time series analysis of climatic variables, such as temperature and precipitation, however, we used producers' perceptions within past 10 years periods. Producers respond to survey questions based on their memory of the recent past and we chose 10 years period as a reference timeframe in this study. Table 1 presents the percentage of respondents who perceived climate change in the past 10 years from 2009 to 2018 (Regmi, 2020). If producers perceived changes in weather patterns, the probability of adopting climate change adaptation practices are high (Nhemachena and Hassan, 2007; Nhemachena et al., 2014; Khanal et al., 2018).

## Empirical model

Theoretically, farmers' adoption intensity of climate change adaptation practices is higher if farmers' utility gained from cumulative effects of five practices is greater than non-adoption. Following Teklewold et al. (2013), we specify the total number of climate change adaptation practices to represent the adoption intensity and hypothesize that access to four types of institutional resources positively influence the farmers' adoption intensity. The number of practices adopted i.e., the adoption intensity may serve as a count variable with an assumption of equal probability of occurrence (Wollni et al., 2010). However, the likelihood of adopting the first practice may differ from adopting additional practices since experienced producers are more exposed to technical information (Teklewold et al., 2013). Therefore, the number of adaptation practices adopted serves as an ordinal variable instead of a count variable. The ordered probit model presented in equations 2–4 as following:

$$\mathrm{Y^*}_{\mathrm{i}} = \mathrm{X'}_{\mathrm{i}}\beta + \varepsilon_{\mathrm{i}} \quad \text{for } \mathrm{j} = 1, .., \mathrm{M} \text{ practices} \tag{2}$$

we define

$$\mathrm{Y_i} = \mathrm{j} \text{ if } \alpha_{\mathrm{j}-1} < \mathrm{Y^*}_{\mathrm{i}} \leq \alpha_{\mathrm{j}} \tag{3}$$

Then,

$$\mathrm{P}\left(\mathrm{Y_i} = \mathrm{j}|\mathrm{X}\right) = 1 - \phi\,\left(\alpha_{\mathrm{j}-1} - \mathrm{X'}_{\mathrm{i}}\beta\right) \tag{4}$$

where $Y*_i$ represents a latent variable (utility of adoption of producer $i$ $(i = 1, \ldots\ldots, N)$) indicating adoption of $j$ number of adaptation practices adopted $\left(j = 1, \ldots\ldots, M\right), X'_i$ is a vector of explanatory variables, $\beta$ is a vector of parameters to be estimated, $\alpha_j$ are threshold parameters (cutoffs), $\varepsilon_i$ is an unobservable error term (normally distributed; zero mean and unitary variance), and $P$ represents probability and $\phi$ is the standard normal cumulative distribution function (cdf). The regression parameters, $\beta$, and threshold parameters (cutoffs), $\alpha_j$, are estimated through maximum likelihood estimation. We use *oprobit* command in STATA 16 to estimate the ordered probit model (StataCorp, 2019). The coefficients from ordered probit estimation indicate how each institutional resource enhances intensity of adoption. Thus, we estimate marginal effects to quantify how each explanatory variables affect intensity of adoption. The marginal effect of change in $X'$ on the likelihood of having $j^{th}$ category is:

$$\frac{\partial \mathrm{P}(\mathrm{Y_i} = \mathrm{j})}{\partial \mathrm{X_i}} = [\phi\,\left(\alpha_{\mathrm{j}-1} - \mathrm{X'}_{\mathrm{i}}\beta\right) - \phi\,\left(\alpha_{\mathrm{j}} - \mathrm{X'}_{\mathrm{i}}\beta\right)]\beta \tag{5}$$

We use the post-estimation command, *mfx* after fitting ordered probit model in Stata 16 to estimate marginal effects.

We hypothesize that access to four institutional resources (i.e., membership, Extension, training, and information) positively influence the producer's decision to adopt climate change adaptation practices. Following Deressa et al. (2009), we hypothesize that access to Extension, and information influence the adoption of climate change adaptation practices. Following Piya et al. (2013), our hypothesis is that membership, training, and information affect the adoption of multiple climate change adaption practices. Likewise, Zamasiya et al. (2017) indicate that access to Extension, information, and membership to social groups enhance the adoption of climate change practices among smallholder producers.

The control variables as a part of $X'_i$ include farmers' and farm characteristics that may influence farmers' decisions to adopt multiple adaptation practices. Farmers' household characteristics such as gender of the household head, household size, years of farming experience, and education level are potential key determinants of adoption (Ali and Erenstein, 2017; Mulwa et al., 2017). We hypothesize that gender of farmers' head of household influences the decision to adopt. Following Deressa et al. (2009), we hypothesize that greater educational attainment of the household head implies better access to information on improved farming practices, and, thus, greater likelihood of adaptation to climate change. A dependency ratio, which is the total number of dependent family members divided by the total number of economically active members in the household, serves as a proxy for household labor availability. A family with a lower dependency ratio has greater availability of labor to adopt additional labor-intensive farming practices (Deressa et al., 2009). We include years of farming of household head to hypothesize that producers with many years of farming experience are more likely to adopt multiple adaptation practices (Deressa et al., 2009). We hypothesize that households whose members have migrated (for employment abroad) can influence the adoption decision in either way (positive and negative). As noted by Hassan and Nhemachena (2008), Nhemachena et al. (2014), Ali and Erenstein (2017), and Mulwa et al. (2017) we hypothesize that household income has a positive effect on adoption as higher income provides opportunities to improve farming practices. We hypothesize that producers are more likely to adopt climate change adaptation practices if they perceived changes in local weather patterns.

Following Nhemachena et al. (2014) and Mulwa et al. (2017) we include farm characteristics such as size and number of parcels as additional factors influencing the adoption of multiple climate change adaptation practices.

## Empirical results and discussion

### Data discussion

We present summary statistics from the data used for the empirical model in Table 2. More than three-fourths of producers (77%) perceived changes in local weather patterns in Chitwan over the past 10 years. Our data indicate that almost a quarter of producers did not adopt any climate change adaptation practice (23%). Among the five climate change adaptation practices, majority of producers adjusted their crop calendar (73%), adopted improved varieties (65%), and invested in irrigation practices (61%), while less than a quarter of producers adopted IPM practices (22%) and DSR practices (16%) in the past 3 years. More than half of producers (54%) had access to local agricultural Extension services and weather-related information through television, radio, mobile phone applications, text messages, or publications in the past year. About 44% of producers participated in climate change adaptation training programs, and more than two thirds of producers (68%) were members of agricultural groups or cooperatives in the past 3 years.

The farmers' demographic characteristics indicate that 20% of heads of farmers' households were female, and the ratio of dependent family members to economically active family members that are working age (16–60 years old) was 0.49. Nearly half (45%) of producers had at least one household member who migrated to another country for employment in the past year. The average education of heads of farmers' households was 7.9 years, the average farming experience of producers was 26.0 years, and average annual household income was equivalent to $2,091 (USD). The rice farm characteristics show that the average number of plots under rice cultivation was 1.65 and average rice cultivated area for each farm was 0.46 hectares (1.137 acres). Over three-fourths of the rice producers (78%) sold rice in their local marketplace in the past year.

### Results from empirical model

We report parameter estimates and marginal effects of the ordered probit model in Table 3. The likelihood ratio chi-squared statistic for the ordered probit model is 324.56, the log-likelihood value is −434.87 and highly significant (Prob $> \chi^2 = 0.000$), indicating that the variables sufficiently explain the ordered probit model and goodness of fit measure of the model with the data. Multicollinearity was assessed by calculating conditional index values for each explanatory variable of the ordered probit model (Belsley, 1991). Multicollinearity can be a concern in regression models with many variables as in the ordered probit model. A condition index value is used to detect multicollinearity (Belsley, 1991). An informal rule of thumb suggests that the condition index value above 30 indicates multicollinearity. The condition index value of our model is 9.48, and thus there is no evidence of multicollinearity among the variables.

The coefficients of the ordered probit model can be interpreted only in terms of their signs, and the magnitudes of the effects of the variables are shown in their marginal effects where all the other covariates are held at the means. Our results indicate that if producers perceive variability in

TABLE 2 Variable descriptions and summary statistics ($n = 359$).

| Variable | Description | Mean | Standard deviation | Expected sign |
|---|---|---|---|---|
| *Climate change adaptation* | | | | |
| Variety | 1 if adoption of drought tolerant and short-duration rice varieties; 0 otherwise | 0.65 | 0.47 | N/A |
| Irrigation | 1 if producer invested in improved irrigation; 0 otherwise | 0.61 | 0.48 | N/A |
| DSR | 1 if adoption of direct seeded rice; 0 otherwise | 0.16 | 0.36 | N/A |
| IPM | 1 if adoption of integrated pest management; 0 otherwise | 0.22 | 0.41 | N/A |
| Adjustment | 1 if adjusted crop planting date; 0 otherwise | 0.73 | 0.44 | N/A |
| *Institutional resources* | | | | |
| Membership | 1 if any household member is a member of a farmers group or cooperative; 0 otherwise | 0.68 | 0.46 | + |
| Extension | 1 if producer contacted Extension agent in the past year; 0 otherwise | 0.54 | 0.50 | + |
| Training | 1 if producer received agricultural training in the past year; 0 otherwise | 0.44 | 0.48 | + |
| Information | 1 if producer received agricultural and weather information through TV/FM radio, phone applications, text messages, and publications; 0 otherwise | 0.54 | 0.49 | + |
| *Demographics* | | | | |
| Gender | 1 if head of the household is female; 0 otherwise | 0.20 | 0.40 | +/− |
| Dependency ratio | Ratio of number of dependent family members to number of economically active family members aged 16–60 years | 0.49 | 0.65 | - |
| Out-migration | 1 if any of household member migrated to another country for employment; 0 otherwise | 0.45 | 0.49 | +/− |
| Education | Formal education years of producer | 7.92 | 4.12 | + |
| Farming years | Years of farming experience of producer | 26.01 | 10.81 | + |
| Income | Annual household Income (USD) | 2,090.90 | 1,472.01 | + |
| *Climate change perception* | | | | |
| Climate | 1 if perceived changes in local weather over the past 10 years; 0 otherwise | 0.77 | 0.42 | + |
| *Farm characteristics* | | | | |
| Rice plots | Number of plots under rice cultivation | 1.65 | 0.79 | + |
| Rice sold | 1 if sold rice in the market; 0 otherwise | 0.78 | 0.41 | + |
| Rice area | Hectares of rice area | 0.46 | 0.30 | +/− |

local weather patterns, the likelihood of adopting more climate change adaptation practices increases. The marginal effects of the variable suggest that changing from unperceived to perceived variability in local weather patterns decreases the probability of not adopting, or adopting one, and two climate change adaptation practices by 17.8, 15.3, and 3.7%, respectively. In contrast, the same change increases the probability of adopting three, four, and five climate adaptation practices by 23.7, 9.9, and 3.2%, respectively.

Our results also indicate that if producers are a member of farmer groups or cooperatives and have access to Extension, training, and information services, their likelihood of adopting multiple climate change adaptation practices increases (see Figure 2). We analyzed and interpreted intensity of adoption as high intensity and low intensity. For example, low intensity includes adoption of one or two climate change adaptation practices and high intensity includes adoption of three or more climate change adaptation practices. Our analysis focuses on examining high intensity of adoption measured by the adoption of three, four, and five climate change adaptation practices. The positive effect of the membership in farmer groups or cooperatives is consistent with literature by Teklewold et al. (2013) and Aryal et al. (2018) who find that membership in farmer groups and cooperatives increases the likelihood of

**TABLE 3** Parameter estimates and marginal effects from ordered probit model (Dependent variable: Climate adaptation intensity).

| Explanatory variable | Coef. | St.Err | Marginal effect | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Prob = (Y=0\|X) | Prob = (Y=1\|X) | Prob = (Y=2\|X) | Prob = (Y=3\|X) | Prob = (Y=4\|X) | Prob = (Y=5\|X) |
| *Institutional resources* | | | | | | | | |
| Membership | 0.410** | 0.178 | −0.059** | −0.072** | −0.028** | 0.090** | 0.051** | 0.017** |
| Extension | 0.595*** | 0.148 | −0.080*** | −0.103*** | −0.044*** | 0.120*** | 0.078*** | 0.029*** |
| Training | 0.407*** | 0.144 | −0.050*** | −0.070*** | −0.033** | 0.077*** | 0.056*** | 0.021** |
| Information | 0.509*** | 0.162 | −0.068*** | −0.088*** | −0.038*** | 0.103*** | 0.067*** | 0.025** |
| *Demographics* | | | | | | | | |
| Gender | −0.294* | 0.150 | 0.042* | 0.052* | 0.020** | −0.066* | −0.036** | −0.012* |
| Dependency ratio | 0.060 | 0.085 | −0.007 | −0.010 | −0.004 | 0.012 | 0.008 | 0.003 |
| Out-migration | −0.042 | 0.120 | 0.005 | 0.007 | 0.003 | −0.008 | −0.005 | −0.002 |
| Education | 0.082*** | 0.021 | −0.010*** | −0.014*** | −0.006*** | 0.016*** | 0.011*** | 0.004*** |
| Farming years | 0.001 | 0.005 | −0.001 | −0.001 | −0.001 | 0.001 | 0.001 | 0.001 |
| Income | 0.001** | 0.000 | 0.001** | −0.001** | −0.001** | 0.001** | 0.001** | 0.001** |
| *Climate change perception* | | | | | | | | |
| Climate | 0.961*** | 0.186 | −0.178*** | −0.153*** | −0.037*** | 0.237*** | 0.099*** | 0.032*** |
| *Farm characteristics* | | | | | | | | |
| Rice plots | 0.111 | 0.086 | −0.014 | −0.019 | −0.009 | 0.022 | 0.015 | 0.005 |
| Rice sold | 0.206 | 0.166 | −0.028 | −0.036 | −0.015 | 0.045 | 0.026 | 0.009 |
| Rice area | −0.269 | 0.213 | 0.034 | 0.047 | 0.022 | −0.054 | −0.036 | −0.013 |

Log-likelihood ratio χ2 (24) = 324.56; Prob > χ2 = 0.000.
Number of observations = 359.
Log-likelihood = −434.87.
***, **, and * refers to significance at 1%, 5%, and 10 % levels, respectively.

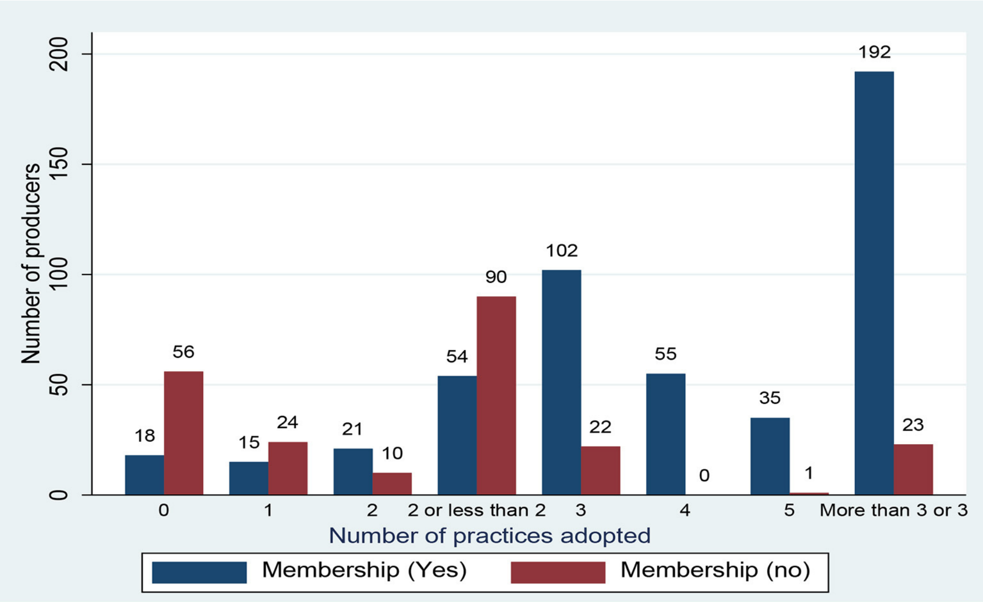


FIGURE 2
Intensity of adoption of climate change adaptation practices across membership status.

adopting climate change adaptation practices such as adopting stress-tolerant crop varieties, crop rotation, and tillage practices. The positive effect of the access to Extension service aligns well with previous studies (FAO, 2003; Etwire et al., 2013; Mulwa et al., 2017; Rickards et al., 2018; Atube et al., 2021) that find educational programs through Extension services help improving the capacity of smallholder producers to mitigate negative impacts of climate change. The positive effect of climate change adaption training implies that producers who attend such training programs are more likely to adapt to climate change by adopting improved crop varieties, adjusting farm calendar, following weather forecasts, and intercropping (Trinh et al., 2018). The positive effect of access to weather information supports previous findings (Mwalukasa, 2013; Upadhyay and Bijalwan, 2015; Islam and Nursey-Bray, 2017; Mulwa et al., 2017; Owusu et al., 2021) that access to climate-related information enhances the likelihood of climate adaptation practices.

The marginal effects of the four institutional resources show that, keeping other covariates at their means, changing from non-member to member of farmer groups or cooperatives and changing from not having to having access to Extension service, training program, and information decrease the likelihood of adopting zero, one, and two climate change adaptation practices. In contrast, the same changes under the same conditions increase the likelihood of adopting three, four, and five climate change adaptation practices. Out of the four institutional resources, access to Extension service has the highest absolute marginal effects across all six climate change adaptation practices. For example, changing from not having to having access to Extension service decreases the likelihood of adopting zero, one, and two climate change adaptation practices by 8.0, 10.3, and 4.4%, respectively. In contrast, the same change increases the likelihood of adopting three, four, and five climate change adaptation practices by 12.0, 7.8, and 2.9%, respectively. Overall, consistent with the findings of Aryal et al. (2018), the likely impact of each institutional factors reduces as the level of intensity increases. For example, access to Extension services enhances the likelihood of adopting three climate change adaptation practices by 12.0% whereas the likelihood of adopting five climate change adaptation practices increase by only 2.9%. These findings indicate that adoption of a greater number of adaptation practices reduced with the increasing availability of multiple adaptation practices.

It is noteworthy to identify that there are consistently negative marginal effects of the four institutional resources when producers do not adopt or up to two climate change adaptation practices (low intensity of adoption) while consistently positive marginal effects of the four institutional resources on three to five adaptation practices (high intensity of adoption). The reason behind this clear and consistent pattern is as follows: our data indicates that majority of producers who have a membership (78%), and have access to Extension service (82%), training program (84%), and information (84%) choose to adopt three or above climate change adaptation practices or high intensity adopters (see Table 4, Figure 2). In contrast, majority of producers who do not have a membership (80%) and do not have access to Extension service (66%), training program (59%), and information (69%) choose not to adopt

TABLE 4 Intensity of adoption (number of practices) based on producer's access to extension, training, and information (institutional resources).

| Intensity of adoption (number of practices) | Producer's access to: | | | | | |
|---|---|---|---|---|---|---|
| | Extension | | Training | | Information | |
| | Yes | No | Yes | No | Yes | No |
| 0 | 6 | 68 | 0 | 74 | 0 | 74 |
| 1 | 14 | 25 | 10 | 29 | 13 | 26 |
| 2 | 15 | 16 | 15 | 16 | 18 | 13 |
| Less than or equal to 2 (low intensity) | 35 | 109 | 25 | 119 | 31 | 113 |
| 3 | 85 | 39 | 69 | 55 | 81 | 43 |
| 4 | 44 | 11 | 39 | 16 | 51 | 4 |
| 5 | 31 | 5 | 25 | 11 | 33 | 3 |
| More than or equal to 3 (high intensity) | 160 | 55 | 133 | 82 | 165 | 50 |

or adopt up to two climate adaptation practices or low intensity adopters.

The parameter estimates and their marginal effects of the control variables are also presented in Table 3. Results reveal that male-headed households are more likely to adopt at least three climate change adaptation practices (high intensity of adoption) compared with households headed by female. Results also show that farmers with higher levels of education and income are less likely to adopt less than two climate change adaptation practices (low intensity of adoption) and more likely to adopt at least three climate change adaptation practices (high intensity of adoption). In contrast, farm characteristics such as number of rice plots, whether harvested rice is sold in market, and rice acreage are not significant factors in the decision to adopt climate change adaptation practices.

We found that 23.4% of producers did not adopt any climate change adaptation practices. We analyzed the potential reasons for smallholder producers not adopting climate change adaptation practices (see Table 5). Results indicate that lack of relevant information and inadequate technical knowledge are two prominent reasons for not adopting improved varieties, DSR, IPM, and adjustment in crop calendar, while affordability is the main reason farmers to not adopt irrigation practices. Overall, we find that for four out of five adaptation practices (except improved irrigation), lack of information and lack of technical knowledge are the most important reasons for not adopting climate change adaptation practices. These findings suggest that improved education and providing technical training along with financial support to producers may improve adoption of climate change adaptation practices.

## Conclusions

This study evaluated the influence of agricultural Extension services, agricultural training, and information on weather and improved farming practices, and membership in producer groups/cooperatives on adoption intensity of climate change adaptation practices. As a case study, we collected smallholder rice producer data in 2019 through household surveys in Chitwan, Nepal. We used an ordered probit model estimation to examine how institutional resources influence adoption intensity of practices.

Smallholder rice producers face many adverse impacts resulting from climate change. Along with reduced yields, the most serious challenges faced by smallholder rice producers in Chitwan include greater incidence of disease, pests, and weeds, delays in rice transplantation, and reduced availability of irrigation water. Smallholder producers adopted several practices to reduce the negative impacts of climate change and variability on rice production. Results indicate that 76.6% of rice producers adopted at least one adaptation practice. Lack of information and technical knowledge on adaptation practices and insufficient financial resources are main reasons for non-adoption of adaptation practices.

The findings indicate that: (1) access to institutional resources significantly enhanced the likelihood of adopting multiple climate change adaptation practices; (2) the adoption of three, four, and five climate change adaptation practices (high intensity of adoption) significantly increased with access to institutional resources; (3) intensity of adoption of climate change adaptation practices reduced with more adaptation alternatives available to smallholder rice producers; and (4) lack of information and technical knowledge are the most important reasons for non-adoption of climate change adaptation practices by smallholder rice producers.

The findings of this study are valuable for policymakers and local agencies to prioritize resource allocation to enhance intensity of climate change adaptation among smallholder rice producers. The results from this study are limited to the intensity of adoption of climate change adaptation practices and have no bearing on the effectiveness or the impact of

TABLE 5 Reasons for non-adoption of climate change adaptation practices (%).

| Reasons for non-adoption | Varieties | Irrigation | DSR | IPM | Crop calendar adjustment |
|---|---|---|---|---|---|
| Lack of information | 41.1 | 7.4 | 41.0 | 47.3 | 32.8 |
| Unable to afford | 15.2 | 59.6 | 2.1 | 4.5 | 11.4 |
| Lack of technical knowledge | 34.2 | 12.1 | 38 | 43.9 | 34.8 |
| Requires more effort/not profitable | 0.9 | 3.3 | 5.1 | 2.4 | 2.7 |
| Not applicable | 4.4 | 17.3 | 13.5 | 1.7 | 17.0 |
| Unavailable | 4.2 | 0.3 | 0.4 | 0.2 | 0 |

the practices. For example, holding other factors at mean, access to Extension services enhanced the likelihood of adopting three, four, and five climate change adaptation practices (high intensity of adoption) by 12.0, 7.8, and 2.9%, respectively, which is higher than the impacts of access to agricultural training services, access to weather information, and membership in producer co-operatives or farmer's groups. Local governments can enhance intensity of adoption by prioritizing resources to Extension services first, followed by access to weather-related information, training support, and membership in producer groups/cooperatives.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

The studies involving human participants were reviewed and approved by Institutional Review Board, University of Tennessee. The patients/participants provided their written informed consent to participate in this study.

## Author contributions

HR led the primary data collection, analyzed the data, conceptualized the model, and contributed to manuscript preparation. SU conceptualized the study, contributed to survey development, data analysis, and contributed to manuscript preparation. S-HC and CC assisted with survey development, data analysis, model estimation, and contributed to manuscript preparation. JM contributed to data analysis and manuscript preparation. All authors contributed to the article and approved the submitted version.

## Acknowledgments

We acknowledge the support and cooperation of rice producers in Chitwan, Nepal. We are grateful to National Institute for Mathematical and Biological Synthesis (NIMBioS), University of Tennessee, Knoxville for providing financial support for travel and to conduct the field survey in Chitwan, Nepal.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1016404/full#supplementary-material

## References

Ali, A., and Erenstein, O. (2017). Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Clim. Risk Manag.* 16, 183–194. doi: 10.1016/j.crm.2016.12.001

Aryal, J. P., Rahut, D. B., Maharjan, S., and Erenstein, O. (2018). *Factors affecting the adoption of Multiple Climate-Smart Agricultural Practices in the Indo-Gangetic Plains of India. Natural Resources Forum.* Oxford, UK: Blackwell Publishing Ltd.

Aryal, J. P., Sapkota, T. B., Khurana, R., Khatri-Chhetri, A., Rahut, D. B., and Jat, M. L. (2020). Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environ. Dev. Sustain.* 22, 5045–5075. doi: 10.1007/s10668-019-00414-4

Atube, F., Malinga, G. M., Nyeko, M., Okello, D. M., Alarakol, S. P., and Okello-Uma, I. (2021). Determinants of smallholder farmers' adaptation strategies to the effects of climate change: evidence from northern Uganda. *Agric. Food Secur.* 10, 1–14. doi: 10.1186/s40066-020-00279-1

Aza, O. (2021). *The Factors Influencing the Leader's Perceptions of Success of Dairy Cooperatives: The Case of Cumbal Nariño Dairy Associations* (Master's Thesis). Tennessee: The University of Tennessee. Available online at: https://trace.tennessee.edu/utk_gradthes/6303/ (accessed November 26, 2022).

Azadi, Y., Yazdanpanah, M., and Mahmoudi, H. (2019). Understanding smallholder farmers' adaptation behaviors through climate change beliefs, risk perception, trust, and psychological distance: Evidence from wheat growers in Iran. *J. Environ. Manage.* 250, 109456. doi: 10.1016/j.jenvman.2019.109456

Bandara, J. S., and Cai, Y. (2014). The impact of climate change on food crop productivity, food prices and food security in South Asia. *Econ. Anal. Policy.* 44, 451–465. doi: 10.1016/j.eap.2014.09.005

Belsley, D. A. (1991). A guide to using the collinearity diagnostics. *Comput. Sci. Rev.* 4, 33–50.

Biggs, E. M., Tompkins, E. L., Allen, J., Moon, C., and Allen, R. (2013). Agricultural adaptation to climate change: observations from the Mid-Hills of Nepal. *Clim. Develop.* 5, 165–173. doi: 10.1080/17565529.2013.789791

Bryan, E., Deressa, T. T., Gbetibouo, G. A., and Ringler, C. (2009). Adaptation to climate change in Ethiopia and South Africa: options and constraints. *Environ. Sci. Policy.* 12, 413–426. doi: 10.1016/j.envsci.2008.11.002

Chhetri, P. (2019). *Personal Communication.* Chitwan, Nepal: Agricultural Officer, Agricultural Knowledge Center (AKC).

Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T., and Yesuf, M. (2009). Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Glob. Environ. Change.* 19, 248–255. doi: 10.1016/j.gloenvcha.2009.01.002

Etwire, P. M., Al-Hassan, R. M., Kuwornu, J. K., and Osei-Owusu, Y. (2013). Smallholder farmers adoption of technologies for adaptation to climate change in Northern Ghana. *J. Agric. Ext.* 5, 121–129. doi: 10.5897/JAERD13.0481

FAO (2003). *World Agriculture Toward 2015/2030.* Rome, Italy: An FAO perspective.

FAO (2014). *Managing Climate Risks and Adapting to Climate Change in the Agriculture Sector in Nepal.* Rome, Italy: Food and Agriculture Organization.

FAO (2020). Rome, Italy: FAOSTAT. Available online at: http://www.fao.org/faostat/en/#data/QC/visualize (accessed November 26, 2022).

Feola, G., Lerner, A. M., Jain, M., Montefrio, M. J. F., and Nicholas, K. A. (2015). Researching farmer behaviour in climate change adaptation and sustainable agriculture: lessons learned from five case studies. *J. Rural Stud.* 39, 74–84. doi: 10.1016/j.jrurstud.2015.03.009

Gadédjisso-Tossou, A. (2015). Understanding farmers' perceptions of and adaptations to climate change and variability: The case of the Maritime, Plateau and Savannah regions of Togo. *Agri. Sci.* 6, 1441–1454. doi: 10.4236/as.2015.612140

Gbetibouo, G. A. (2009). "Understanding farmers' perceptions and adaptations to climate change and variability, the case of the Limpopo Basin, South Africa," *In International Food Policy Research Institute (IFPRI) Discussion Paper No. 00849*. Washington D.C. USA: Environment and Production Technology Division, International Food Policy Research Institute.

Gumma, M. K., Gauchan, D., Nelson, A., Pandey, S., and Rala, A. (2011). Temporal changes in rice-growing area and their impact on livelihood over a decade: a case study of Nepal. *Agricult. Ecosyst. Environ.* 2, 382–392. doi: 10.1016/j.agee.2011.06.010

Gurung, G. B., and Bhandari, D. (2009). Integrated approach to climate change adaptation. *J. Forest Livelihood.* 8, 91–99. Available online at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-79956061397&partnerID=40&md5=418591d7238733208a103ffbb77115d4

Harvey, C. A., Rakotobe, Z. L., Rao, N. S., Dave, R., Razafimahatratra, H., Rabarijohn, R. H., et al. (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philos. Trans. R. Soc.* 369, 20130089. doi: 10.1098/rstb.2013.0089

Hassan, R. M., and Nhemachena, C. (2008). Determinants of African farmers' strategies for adapting to climate change: multinomial choice analysis. *African J. Agric. Resour. Econ.* 2, 83–104. doi: 10.22004/ag.econ.56969

IPCC. (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, eds P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley (Cambridge; New York, NY: Cambridge University Press). p. 896. doi: 10.1017/9781009157988

Islam, M. T., and Nursey-Bray, M. (2017). Adaptation to climate change in agriculture in Bangladesh: the role of formal institutions. *J. Environ. Manage.* 200, 347–358. doi: 10.1016/j.jenvman.2017.05.092

Karna, P. K. (2014). "The impact of climate change on rice production in Nepal," in *Working paper, South Asian Network for Development and Environmental Economics.* Kathmandu, Nepal.

Khanal, U., Wilson, C., Hoang, V. N., and Lee, B. (2018). Farmers' adaptation to climate change, its determinants and impacts on rice yield in Nepal. *Ecol. Econ.* 144, 139–147. doi: 10.1016/j.ecolecon.2017.08.006

Krejcie, R. V., and Morgan, D. W. (1970). Determining sample size for research activities. *Educ. Psychol. Meas.* 30, 607–610. doi: 10.1177/001316447003000308

Kurukulasuriya, P., and Rosenthal, S. (2013). *Climate Change and Agriculture: A Review of Impacts and Adaptations.* Agricultural and Rural Development Department, World Bank. Available online at: https://openknowledge.worldbank.org/handle/10986/16616 (accessed November 26, 2022).

Manandhar, S., Vogt, D. S., Perret, S. R., and Kazama, F. (2011). Adapting cropping systems to climate change in Nepal: a cross-regional study of farmers' perception and practices. *Reg. Environ. Change.* 11, 335–348. doi: 10.1007/s10113-010-0137-1

McSweeney, C., New, M., Lizcano, G., and Lu, X. (2010). The UNDP Climate Change Country Profiles: improving the accessibility of observed and projected climate information for studies of climate change in developing countries. *Bull. Am. Meteorol. Soc.* 91, 157–166. doi: 10.1175/2009BAMS2826.1

Ministry of Energy, Water Resources, and Irrigation. (2018). *Way Forward of Energy, Water Resources, and Irrigation.* Kathmandu: Consumer Information Platform.

MoAD. (2015). *Selected Indicators of Nepalese Agriculture and Population.* Kathmandu: Government of Nepal.

MoE. (2010). *National Adaptation Plan of Action to Climate Change.* Kathmandu: Government of Nepal.

MOF. (2014). *Economic Survey. Fiscal Year 2013/14.* Kathmandu: Government of Nepal.

MOF. (2018). *Economic Survey. Fiscal Year 2017/18.* Kathmandu: Government of Nepal.

Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. *Proc. Nat. Acad. Sci.* 104, 19680–19685. doi: 10.1073/pnas.0701855104

Mulwa, C., Marenya, P., and Kassie, M. (2017). Response to climate risks among smallholder farmers in Malawi: a multivariate probit assessment of the role of information, household demographics, and farm characteristics. *Clim. Risk Manag.* 16, 208–221. doi: 10.1016/j.crm.2017.01.002

Mwalukasa, N. (2013). Agricultural information sources used for climate change adaptation in Tanzania. *Library Rev.* 62, 266-292. doi: 10.1108/LR-12-2011-0096

National Planning Commission, Nepal. (2020). *Fifteenth Plan. Fiscal Year 2019/20-2023/24.* Kathmandu, Nepal.

Nhemachena, C., and Hassan, R. (2007). *Micro level analysis of farmers' adaptation to climate change in Southern Africa. IFPRI Discussion Paper No. 00714.* International Food Policy Research Institute, Washington, DC, United States.

Nhemachena, C., Hassan, R., and Chakwizira, J. (2014). Analysis of determinants of farm-level adaptation measures to climate change in Southern Africa. *J. Dev. Agric. Econ.* 6, 232–241. doi: 10.5897/JDAE12.0441

Owusu, V., Ma, W., Renwick, A., and Emuah, D. (2021). Does the use of climate information contribute to climate change adaptation? Evidence from Ghana. *Clim. Dev.* 13, 616–629. doi: 10.1080/17565529.2020.1844612

Piya, L., Maharjan, K. L., and Joshi, N. P. (2013). Determinants of adaptation practices to climate change by Chepang households in the rural Mid-Hills of Nepal. *Reg. Environm. Chang.* 13, 437–447. doi: 10.1007/s10113-012-0359-5

Regmi, H. P. (2020). *Climate Change and Variability: Producers' Perceptions and Determinants of Adaptation Strategies in Rice Farming in Chitwan, Nepal* (Master's Thesis). Tennessee: University of Tennessee. Available online at: https://trace.tennessee.edu/utk_gradthes/6246/ (accessed November 26, 2022).

Regmi, H. P., Upendram, S., Cho, S.-H., and Clark, C. D. (2022). Examining complementarity relationships among climate change adaptation practices of rice producers in Chitwan, Nepal. *Clim. Dev.* 1–21. doi: 10.1080/17565529.2022.2107980

Rickards, L., Alexandra, J., Jolley, C., and Frewer, T. (2018). *Final Report: Review of Agricultural Extension.* Canberra, ACT, Australia: Australian Centre for International Agricultural Research (ACIAR).

Sarker, M. A. R., Alam, K., and Gow, J. (2014). Assessing the effects of climate change on rice yields: an econometric investigation using Bangladeshi panel data. *Econ. Anal. Policy* 44, 405–416. doi: 10.1016/j.eap.2014.11.004

Singh, K. N. (1997). "Agricultural extension education" in *Handbook of Agriculture, Indian Council of Agricultural Research, 5th Edn* (New Delhi: Indian Council of Agricultural Research), p. 668–703.

Smit, B., and Wandel, J. (2006). Adaptation, adaptive capacity, and vulnerability. *Glob. Environ. Change* 16, 282–292. doi: 10.1016/j.gloenvcha.2006.03.008

StataCorp (2019). *Stata Statistical Software: Release 16*. College Station, TX: StataCorp LLC.

Tazeze, A., Haji, J., and Ketema, M. (2012). Climate change adaptation strategies of smallholder farmers: the case of Babilie District, East Harerghe Zone of Oromia Regional State of Ethiopia. *J. Econ. Sustain. Dev.* 3, 1–12. Available online at: https://scholar.google.com/scholar?cluster=18176727552038859967&hl=en&as_sdt=0,15

Teklewold, H., Kassie, M., and Shiferaw, B. (2013). Adoption of multiple sustainable agricultural practices in rural Ethiopia. *J. Agric. Econ.* 64, 597–623. doi: 10.1111/1477-9552.12011

Thinda, K. T., Ogundeji, A. A., Belle, J. A., and Ojo, T. O. (2020). "Understanding the adoption of climate change adaptation strategies among smallholder farmers: Evidence from land reform beneficiaries in South Africa." In *Land Use Policy 99*. Available online at: https://doi.org/10.1016/j.landusepol.2020.104858 doi: 10.1016/j.landusepol.2020.104858

Tilahun, B., and Bedemo, A. (2014). Farmers' perception and adaptation to climate change: Heckman's two stage sample selection model. *Ethiop. J. Environ. Stud. Manag.* 7, 832–839. doi: 10.4314/ejesm.v7i2.3S

Trinh, T. Q., Rañola Jr, R. F., Camacho, L. D., and Simelton, E. (2018). Determinants of farmers' adaptation to climate change in agricultural production in the central region of Vietnam. *Land Use Policy.* 70, 224–231. doi: 10.1016/j.landusepol.2017.10.023

Upadhyay, A. P., and Bijalwan, A. (2015). Climate change adaptation: services and role of information communication technology (ICT) in India. *Am. J. Environ. Protect.* 4, 70–74. doi: 10.11648/j.ajep.20150401.20

Wheeler, T., and Von Braun, J. (2013). Climate change impacts on global food security. *Science.* 341, 508–513. doi: 10.1126/science.1239402

Wollni, M., Lee, D. R., and Thies, J. E. (2010). Conservation agriculture, organic marketing, and collective action in the Honduran hillsides. *Agri. Econ.* 41, 373–384. doi: 10.1111/j.1574-0862.2010.00445.x

Zamasiya, B., Nyikahadzoi, K., and Mukamuri, B. B. (2017). Factors influencing smallholder farmers' behavioural intention towards adaptation to climate change in transitional climatic zones: A case study of Hwedza District in Zimbabwe. *J. Environ. Manage.* 198, 233–239. doi: 10.1016/j.jenvman.2017.04.073

Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 15 February 2023
DOI 10.3389/fsufs.2023.1010527

EDITED BY
Rupak Goswami,
Ramakrishna Mission Vivekananda Educational and Research Institute, India

REVIEWED BY
Sanjit Maiti,
National Dairy Research Institute (ICAR), India
Uttam Khanal,
Tribhuvan University, Nepal

*CORRESPONDENCE
K. Viswanatha Reddy
✉ vishu.uas@gmail.com
Venkatesh Paramesha
✉ parameshagron@gmail.com

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 03 August 2022
ACCEPTED 03 January 2023
PUBLISHED 15 February 2023

CITATION
Kumar KNR, Reddy MJM, Reddy KV, Paramesha V, Balasubramanian M, Kumar TK, Kumar RM and Reddy DD (2023) Determinants of climate change adaptation strategies in South India: Empirical evidence. *Front. Sustain. Food Syst.* 7:1010527. doi: 10.3389/fsufs.2023.1010527

# Determinants of climate change adaptation strategies in South India: Empirical evidence

K. N. Ravi Kumar[1], M. J. Mohan Reddy[2], K. Viswanatha Reddy[3,4]*, Venkatesh Paramesha[5]*, M. Balasubramanian[6], T. Kiran Kumar[3,4], R. Mohan Kumar[7] and D. Damodar Reddy[3,4]

[1]Department of Agriculture Economics, Achraya N. G. Ranga Agricultural University, Bapatla, Andhra Pradesh, India, [2]Extension Education Institute, Professor Jayashankar Telangana State Agricultural University, Hyderabad, Telangana, India, [3]PME Cell, Indian Council of Agricultural Research–Central Tobacco Research Institute, Rajahmundry, Andhra Pradesh, India, [4]Division of Crop Production, Indian Council of Agricultural Research–Central Tobacco Research Institute, Rajahmundry, Andhra Pradesh, India, [5]Natural Resource Management, Indian Council of Agricultural Research–Central Coastal Agricultural Research Institute, Velha Goa, Goa, India, [6]Division of Agricultural Economics, Indian Council of Agricultural Research-Indian Agricultural Research Institute, New Delhi, India, [7]Department of Agronomy, All India Coordinated Research Project on Castor, University of Agricultural Sciences, Bengaluru, India

The phenomena of climate change pose multifaceted challenges to crop and livestock farming, with severe implications on smallholder farmers' income and livelihoods. Climate change has profound implications (economic, environmental, and social) predominantly on rainfed regions in developing countries like India, where agriculture constitutes the backbone of the economy. In this context, the current study analyzes how farmers perceive climate change in the rainfed ecosystem in India, farmers' adaptation strategies, and their major determinants in addressing climate change. Data were collected from 400 sample farmers in South India. Discriminant and multinomial logit models were employed to identify the adaptation strategies of the farmers. It was evident that the factors such as off-farm income, farm income, and farming experience significantly influenced the adaptation strategies for tackling climate change. Furthermore, access to climate change information and literacy level are vital determinants in different climate change adaptation strategies, including crop diversification, integrated farming system, contingency plans for farm operations, and adoption of soil and water conservation techniques. However, the study highlights the increasing role of institutions (government and private) in future to safeguard the interests of farmers by offering a wide range of policy, research, and technology interventions. In a nutshell, R&D focus on climate-resilient agriculture, application of ICTs in agro-advisory services, and creation off-farm employment opportunities for the farmers is crucial to sustaining their livelihoods as these serve as potential mitigation strategies to impart resilience to climate-sensitive sectors like agriculture in rainfed ecosystems in India or any other countries.

KEYWORDS

**climate change, climate resilience, rainfed ecosystem, small farm holders, sustainability**

## Introduction

Climate change jeopardizes long-term agricultural development, which is dependent on three layers of environmental, economic, and social effects that are all integrated. The significance of agriculture emanates from the fact that it is vital to the economic growth of developing countries, serving as the backbone of their economies by providing food, fiber, raw materials, and employment opportunities to the major chunk of the population (Ogen, 2007). Agriculture is the prime source of sustainable food and nutrition, which is extremely dependent on and influenced by weather and harsh climatic manifestations (Mjelde et al., 1989; Das, 2005; Motha and Murthy, 2007; Sivakumar, 2011; CIE, 2014). Climate change has harmed crop production and productivity in major agricultural regions around the world in recent decades (Almaraz et al., 2008; Reidsma et al., 2009). Moreover, the negative effects of climate change on agricultural production have resulted in high poverty rates (Mendelsohn et al., 2006) and global food insecurity (Das, 2005; Rosenzweig and Tubiello, 2007; Nelson et al., 2009; Misra, 2012; Connoly-Boutin and Smit, 2015). Conversely, a smallholder farmer possesses limited resources or capacity to adapt to climate change (Verchot et al., 2007). However, developing countries have a lower adaptive capacity and do not have the advanced technology to mitigate climate change (Lotze-Campen and Schellnhuber, 2009). Crop production fluctuations have an impact on food availability, prices, and farm revenues, all of which bewilder rural economic advancement. According to some estimates, annual agricultural revenue losses due to climate change in India are predicted to be in the range of 15–18%, rising to 20–25% for unirrigated areas (Government of India, 2017).

Agriculture is the socioeconomic foundation for achieving food security, which is based on the elimination of extreme poverty and hunger (Von Braun et al., 2005). In rural and marginal areas, agriculture is critical to community livelihoods. In this context, agricultural policies and government interventions in rural communities are essential tools for poverty reduction as part of an inclusive approach to economic and social development (Croppenstedt et al., 2018). Nevertheless, climate change, according to the IPCC (2013), affects people's livelihoods, agriculture, freshwater supplies, and other natural resources, which are vital to human survival. Climate change affects crop output, particularly among vulnerable people in rural areas, such as smallholder farmers who rely on rainfed agriculture for a living (Turpie and Visser, 2013). Given the emerging importance of climate change, various studies have been conducted to establish the effects of climate change on farm productivity and describe farmers' climate change adaptation strategies (CCAS) in a particular region. Shrestha et al. (2012) examined the effects of climate change on winter and summer paddy yields in the central area as well as numerous CCAS in Vietnam. Changing planting dates, supplemental irrigation, correct nutrient management, and switching to new rice varieties are among the probable adaptive options for rice cultivation in the region (Shrestha and Bui, 2015). However, some farmers resorted to adaptive practices in the region in response to climate change, for instance, altering transplanting dates and introducing supplementary irrigation.

Climate-resilient agriculture (CRA) is being encouraged to enable climate change adaptation and mitigation. Environmental changes, including climate change, land-use change, and natural resource degradation, have aggravated the vulnerability of agricultural production across the countries in the world. Among these, climate change has emerged as the biggest developmental challenge, especially for developing countries like India, by disrupting the normal socioeconomic settings, particularly of poor people (Narain et al., 2009). Its adverse effects are much more severe on the agricultural sector in affecting both food and nutrition security and sustainable development. Therefore, it is imperative on the part of farmers to face climate change in agriculture by following various adaptation strategies that demand collaborative efforts from different stakeholders. Of course, the major driving force for taking up climatic adaptation strategies comes from farmers' perceptions to tackle the climate change phenomenon.

The review of the literature identifies adaptation to climate change as an established strategy that is thoroughly tangled with developmental activities (Agrawala and Lemos, 2015; Anik et al., 2021; Mushore et al., 2021). India experienced a series of droughts (Figure 1), and the one in 1987 was one of the worst, with an overall rainfall deficiency of 19%, which affected 60% of the normal cropped area and a population of 285 million. This was repeated in 2002 when the overall rainfall deficiency for the country as a whole was again 19%. Over 300 million people spread over 18 states are affected by drought along with around 150 million cattle. Food grain production registered an unprecedented steep fall of 29 million tons. Subsequently, the drought in 2018 is considered the second most severe one, affecting ∼42% of the land area and 500 million people (almost 40% of the country's population). With the advent of climate change since the 1990s (Narain et al., 2009), failed monsoon is the primary reason for frequent droughts in India. Since it is not possible to avoid the adverse impacts of climate change (Figure 2), it is vital to promote adaptation strategies among the farmers to mitigate it in their farm fields. Before this, it is essential to analyze their perceptions about CCAS and determinants of the same for their effective implementation. The past studies, conducted in South Africa (Tshikororo et al., 2021), Ghana (Mwinkom et al., 2021), Ethiopia (Belay et al., 2017), Uganda (Nabikilo et al., 2012), and Fiji (Asafu-Adjaye, 2008), highlighted that farmers changed their cultivation practices as adaptation strategies in various ways, including change in crop calendar, crop varieties, farm machinery for cultivation practices, crop diversification, integrating crops with livestock (farming systems approach), and soil and water conservation practices. Even strategies such as the System of Rice Intensification (SRI)—an innovative method of rice cultivation and microirrigation, were adopted by the farmers to combat water scarcity conditions. They also implemented strategies for coping with declining soil productivity by increasing organic manure application, compost making and application, crop rotation, and crop residue retention (Belay et al., 2017; Tshikororo et al., 2021). In India, the government started promoting the formation of Farmer Producer Organizations when a single farmer could not afford adaptation strategies (Singh et al., 2019). However, the study conducted by Niles et al. (2016) revealed an interesting finding that the farmers' attitudes and perceptions toward climate change do not correlate with their actual adoption. Climate change jeopardizes long-term agricultural development, which is dependent on three layers of environmental, economic, and social effects that are all merging. Climate change not only is an environmental issue but also has significant economic and social implications, particularly for emerging countries that are particularly sensitive, offering significant challenges to their agricultural development and wellbeing (Tesfahunegn et al., 2016).

From the growing body of literature, it is evident that the agriculture sector is heavily impacted by changing climatic circumstances (Lobell et al., 2011; Auffhammer and Schlenker, 2014; Campbell et al., 2016; Khanal and Mishra, 2017), the severity of which is expected to worsen shortly (Lobell et al., 2011; Auffhammer and Schlenker, 2014; Campbell et al., 2016; Khanal and Mishra, 2017). Furthermore, crop productivity levels are harmed by weather incongruities and sudden onset of extremes (dry spells, droughts, and floods) (IPCC, 2012, 2014) due to pest and disease outbreaks (Easterling et al., 2007; Gornall et al., 2010), changes in soil fertility

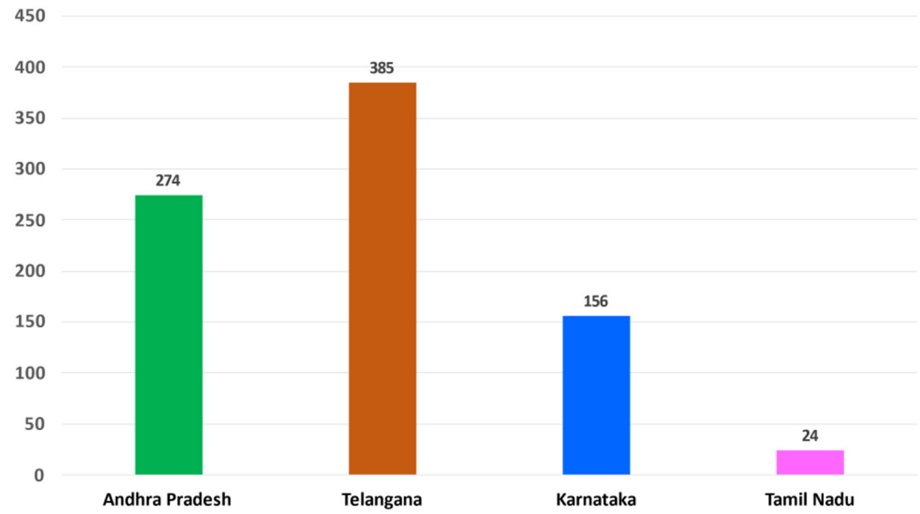
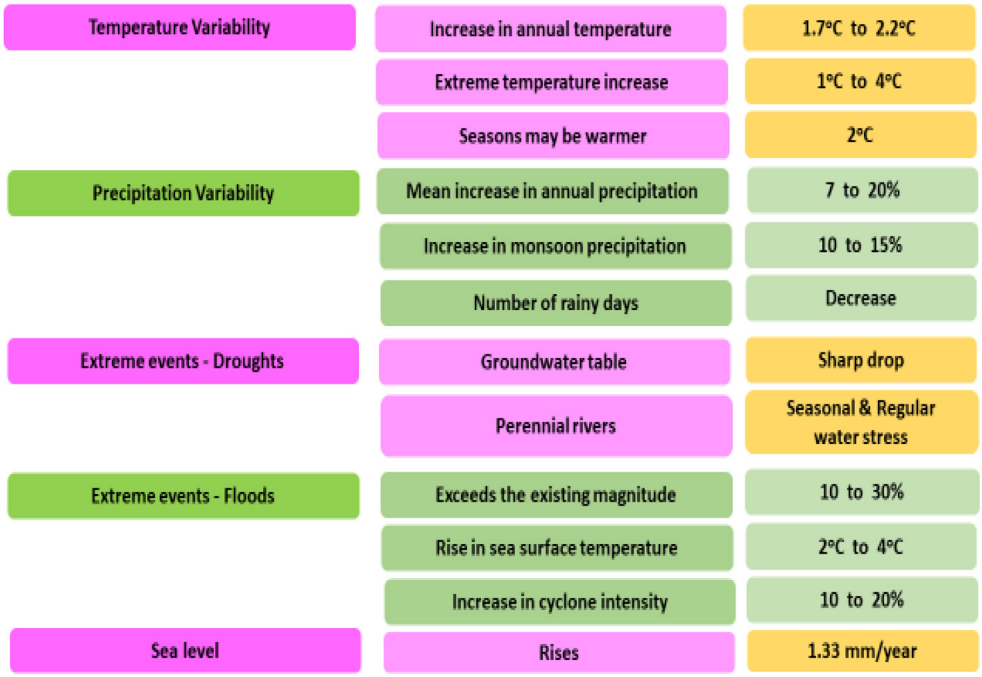


FIGURE 1
Number of Mandals declared drought in the southern states of India, 2019 (Source: Statistical Abstracts of selected States, 2020).



| | | |
|---|---|---|
| Temperature Variability | Increase in annual temperature | 1.7°C to 2.2°C |
| | Extreme temperature increase | 1°C to 4°C |
| | Seasons may be warmer | 2°C |
| Precipitation Variability | Mean increase in annual precipitation | 7 to 20% |
| | Increase in monsoon precipitation | 10 to 15% |
| | Number of rainy days | Decrease |
| Extreme events - Droughts | Groundwater table | Sharp drop |
| | Perennial rivers | Seasonal & Regular water stress |
| Extreme events - Floods | Exceeds the existing magnitude | 10 to 30% |
| | Rise in sea surface temperature | 2°C to 4°C |
| | Increase in cyclone intensity | 10 to 20% |
| Sea level | Rises | 1.33 mm/year |

FIGURE 2
Climate change projections for India by 2030 (compiled by Narain et al., 2009).

(Tang et al., 2008; St Clair and Lynch, 2010), moisture content, and most importantly, water quality and resources (Food and Agriculture Organization, 2011; Misra, 2014; Malek et al., 2018). In Italy, for example, farmer innovation has been found to have a favorable impact on the adoption of water-saving devices (Pino et al., 2017). This reflects process innovation at the farm level, which is the act of adopting new farm methods and putting new information into action (Barzola Iza and Dentoni, 2020). Therefore, it is equally important to analyze the determinants of different climatic adaptation strategies being followed by the farmers in addition to their perceptions to tackle the climate change phenomenon.

## Factors influencing farmers' climate change adaptation

Climate change adaptations are greatly influenced by socioeconomic and environmental indicators. The earlier studies identified the unpredictability of weather, high farm input cost, and lack of access to timely weather information and water resources as the major constraints of farmers' adaptation to climate change. Ndamani and Watanabe (2016) analyzed socioeconomic factors that influence farmers' adaptation to climate change in agriculture and opined that education, household size, annual household income, access to information, credit, and membership in farmer-based organizations as the most important factors that influence farmers' adaptation to climate change. Similarly, Belay et al. (2017) analyzed the smallholder farmers' CCAS and the determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. The findings of the study revealed that the farmers' capacity to choose effective adaptation options was influenced by household demography, as well as positively by farm size, income, access to markets, access to climate information, extension, and livestock production. Zizinga et al. (2017) analyzed the household determinants that contribute to CCAS in the Mount Rwenzori area of southwestern Uganda. The study concluded the use of different crop varieties; tree planting, soil and water conservation, early and late planting, and furrow irrigation are the major adaptation practices. The findings of the discrete choice model indicated that the age of the household head, experience in farming, household size, climate change shocks, land size, use of agricultural inputs, landscape position (location), and crop yield varied significantly ($p > 0.05$) and influenced farmers' choice of CCAS. Mwinkom et al. (2021) investigated the factors influencing adaptation strategies to climate change in the Black Volta Basin of Ghana. The multivariate probit model revealed that gender, age, household size, farmer-based organization membership, farm income, years of education, districts of the location of respondents, farm size, and climate change awareness are the major factors that influenced households' adaptation to the changing climate. Tshikororo et al. (2021) analyzed the farmers' socioeconomic characteristics in tackling climate change in Limpopo Province, South Africa. The study concluded that formal education, agricultural education, age group, farming experience, and off-farm occupation significantly contributed to farmers' perception regarding tackling climate change.

In summary, inadequate information on adaptation methods and financial constraints are the major barriers to adaptation. Considering the above facts in view, there is a need to support the indigenous adaptation strategies with a wide range of institutional, policy, and technological support. At the same time, creating opportunities for non-farm income sources is equally important, as these kinds of activities are less sensitive to climate change. In addition, providing climate change information, extension services, and creating access to markets is also crucial in tackling the impact of climate change on agriculture. Furthermore, there is an urgency in improving household heads' adaptive capacity through education and capacity building, and increasing investments in climate-resilient programs by governmental and non-governmental organizations should deserve special attention. Understanding the elements that influence farmers' decisions to choose one of the available adaptive methods might give a strong foundation for drafting policy suggestions that are sensitive to climatic change (Piya et al., 2013).

Despite the high frequency of climate-induced risks in farming, no research has identified the elements influencing farmers' adaptive choices in agricultural production in the rainfed region of South India under changing climate conditions. This study was focused on a better understanding of perceptions and practices followed by the farmers to tackle climate change in four southern states, namely, Andhra Pradesh, Telangana, Tamil Nadu, and Karnataka. As no prior research on these lines was conducted earlier in South India, this study certainly contributes to the existing literature on farmers' perceptions as one of the major critical elements to dealing with climate change and identifying major determinants for practicing various adaptation strategies. Accordingly, the objective of this study was how and in what way the key determinants related to farm households influence their CCAS in the region.

# Methodology

## Study area and method of data collection

This study was based on the primary and secondary data, conducted in southern states of India, *viz.,* Andhra Pradesh, Telangana, Tamil Nadu, and Karnataka. Nearly half of South India's population is engaged in agriculture, which was largely dependent on monsoon rains. Moreover, South Indian states occupied prominent positions in the cultivation of major crops such as paddy, maize, groundnut, chickpeas, urad, cotton, chilies, sunflower, tobacco, tomato, banana, cashew, coconut, and cardamom in the country. More than half of the gross area sown across these states, *viz.,* Andhra Pradesh (52%), Telangana (63%), Tamil Nadu (54%), and Karnataka (75%), is under rainfed condition. Furthermore, in these states, more than 80 % of farmers belong to marginal and small farmers. From each state, one district was selected purposively, based on the consultations held with local agricultural officers, where it was largely affected by drought and other climate change parameters. In this regard, we purposively selected one district from each state like from Andhra Pradesh (Ananthapuramu, 540 mm), Telangana (Jogulamba Gadwal, 533 mm), Tamil Nadu (Tiruppur, 600 mm), and Karnataka (Chitradurga, 507 mm). From each district, one Mandal was selected (Ananthapuramu (Kalyandurg); Jogulamba Gadwal (Gattu Mandal); Tiruppur (Dharapuram Mandal); and Chitradurga (Challakere Mandal) in accordance with the adoption of CCAS by the farmers and from each Mandal, 100 sample farmers were selected at random. According to Yamane (1967), the minimum sample size in the study should be as follows:

$$n = \frac{Z^2 p(1-p)}{e^2} = \frac{((1.96)^2\, 0.5(1-0.5)}{0.05^2} = 384.16 \qquad (1)$$

Therefore, this study involved a cross-sectional survey of 400 sample farmers at 100 random farmers from each of the above four districts during 2019–2020 (Table 1). Data were collected relating to farmers' perceptions toward tackling climate change and identification of major determinants of farmers' CCAS (drought coping) in the study area. A structured questionnaire was employed among the sample farmers with assistance from local agricultural officers, who interacted directly with the farmers in their respective working locations. In the present context, two groups of farmers were made, *viz.,* farmers willing to tackle climate change (Yes = 1) and farmers not willing to tackle climate change (No = 0). As per the survey, 256 farmers were willing and practicing CCAS and the remaining 144 farmers were not willing to tackle climate change. The socioeconomic characteristics of sample farmers (Table 2) were hypothesized to contribute to discriminating between the two categories of farmers.

**TABLE 1** Number of farmers practicing crops and allied enterprises in the study area.

| No. of farmers | Enterprises practiced |
|---|---|
| 71 | Paddy + Groundnut |
| 119 | Paddy + Paddy + allied enterprise |
| 68 | Paddy + Chickpea + allied enterprise |
| 48 | Paddy + Urad |
| 43 | Groundnut + allied enterprise |
| 51 | Cotton |

**TABLE 2** Description of explanatory variables used in the discriminant analysis.

| Variable | Name | Type of measure | Expected sign |
|---|---|---|---|
| X1 | Farming experience (FE) | Quantitative variable (years) | + |
| X2 | Training on climate change adaptation strategies (TRG) | Dummy (0 = No, 1 = Yes) | + |
| X3 | Age of the farmer (AGE) | Quantitative variable (years) | + |
| X4 | Access to extension contacts (AEC) | Dummy (0 = No, 1 = Yes) | + |
| X5 | Off-farm income (OFFI) | Quantitative variable (Rs/–) | + |
| X6 | Farm size (FS) | Quantitative variable (hectares) | + |
| X7 | Farm Income (FI) | Quantitative variable (Rs/–) | + |

Dependent variable: climate change adaptation strategies (CCAS): dummy; (1 = Yes, 0 = No).

## Empirical models

A discriminant and multinomial logit model was employed to assess the factors influencing farmers' adoption and intensity of adoption of CCAS at the farm level in South India.

### Discriminant analysis

This multivariate statistical technique was employed (Duong et al., 2017; Tshikororo et al., 2021) to classify the farmers into two (or more) mutually exclusive and exhaustive groups based on a set of independent variables, that is, the discriminant model was used to distinguish between two categories of farmers: (i) willing to tackle climate change and (ii) non-willing to tackle climate change coded as 1 and 0, respectively. These two possible categories were defined by several factors, which simultaneously influence the farmers' willingness to tackle climate change. The information related to independent variables (Table 1) used to calculate discriminant score Z for a given farmer is as follows:

$$\begin{aligned} Z_i \;=\; & \beta_0 + \beta_1^* X_1 + \beta_2^* X_2 + \beta_3^* X_3 + \beta_4^* X_4 + \beta_5^* X_5 \\ & + \beta_6^* X_6 + \beta_7^* X_7 + \varepsilon \end{aligned} \tag{2}$$

where Z is the discriminant score that maximizes the distinction between the two categories.

Before running a discriminant analysis, the data used must be independent and normally distributed (Khemakhem nd Boujelbene, 2015). Therefore, the Kolmogorov–Smirnov test was employed to prove the data are normally distributed (Supplementary Table 4). Furthermore, multicollinearity among the independent variables was tested by computing Pearson's correlation matrix (Supplementary Table 5). As the highest absolute value of the correlation coefficient between each variable is <0.7, the multicollinearity problem was ruled out in this study. In the next step, a discriminant analysis (direct method) was applied to the sample data on explanatory variables.

### Multinomial logit model

To analyze the determinants of practicing different climate change adaptation strategies such as crop diversification (a shift toward drought-resistant crops), integrating crops with livestock, changing planting date, and adoption of soil and water conservation practices, the multinomial logistic model was employed (Asrat and Simane, 2018; Diallo et al., 2020; Aryal et al., 2021; Kosoe and Ahmed, 2022). These strategies were prioritized based on the informal discussions held with local Agricultural Department officials of selected Mandals. The description and expected signs of explanatory variables used in this study are presented in Table 3. The estimation of the multinomial logistic model was conducted by normalizing one category, which is named as the "base category." The adaptation measures were grouped into four major categories because farmers used more than one strategy, and the base category was "No adaptation strategy," that is, climate change adaptation strategy—the dependent variable (Dummy), 4 = crop diversification, 3 = integrating crop with livestock, 2 = change planting date, 1 = adoption of soil and water conservation practices, and 0 = no adaptation strategy. These measures were identified based on the discussions held with local agricultural officers and officials from the Department of Agriculture. The officials were recommending these strategies for the farmers to combat the climate change scenario. Not all the farmers were the adopters of these four strategies. Therefore, we assigned ranks to the strategies depending on their priority in the study area as emphasized by local agricultural officers. These adaptation strategies refer to changes in practices followed by the farmers to moderate potential damages or to benefit from opportunities associated with climate change. These prioritized CCAS can help decrease climate risk *via* major risk factors, *viz*., low rainfall, unseasonal rainfall, vulnerability, and exposure. Therefore, the adverse impacts of climate risks may be reduced with the help of these strategies and thus ensure farmers' resilience, reduce vulnerability, and at the same time lead to stabilized annual income. They further guide the farmers to respond to the impacts of climate change that were already affecting them, as well as prepare for future impacts.

# Results and discussion

## Descriptive statistics of the farmers

The description of both the dependent and the explanatory variables included in the model (see Supplementary Tables 1–3)

TABLE 3 Description of explanatory variables used in the multinomial logistic model.

| Variable | Name | Type of measure | Expected sign |
|---|---|---|---|
| X1 | Farming experience (FE) | Quantitative variable (years) | + |
| X2 | Training on climate change adaptation strategies (TRG) | Dummy (0 = No, 1 = Yes) | + |
| X3 | Age of the farmer (AGE) | Quantitative variable (Years) | +/– |
| X4 | Access to extension contacts (AEC) | Dummy (0 = No, 1 = Yes) | + |
| X5 | Off-farm income (OFFI) | Quantitative variable (Rs/-) | + |
| X6 | Farm size (FS) | Quantitative variable (acres) | +/– |
| X7 | Farm income (FI) | Quantitative variable (Rs/–) | + |
| X8 | Access to climate information (AC) | Dummy (0 = No, 1 = Yes) | + |
| X9 | Access to market (AM) | Dummy (0 = No, 1 = Yes) | + |
| X10 | Education (EDU) | Quantitative variable (Years) | + |
| X11 | Livestock ownership (LO) | Dummy (0 = No, 1 = Yes) | + |

estimations is presented in this section. The dependent variables were the adoption and determinants of adaptation strategies employed by farmers in rainfed regions of South India. The study stretches its empirical description from the studies of determinants of the adoption of CCAS (Abdulai and Huffman, 2014; Kibue et al., 2016; Mulwa et al., 2017; Ojo and Baiyegunhi, 2019). The description of explanatory variables and their respective means and the standard deviation is presented in Table 4. The socioeconomic attributes, *viz.*, age, literacy level, farm size, farm income, and off-farm income, were included in the model to control farm household heterogeneity. The descriptive analysis revealed a mean age of 45 years with a standard deviation (SD) of 7.97 for farmers who are practicing climate adaptation strategies and a mean age of 44 years and an SD of 8.09 for farmers not willing to take up climate adaptation strategies. Among the factors such as the number of training (TRG) received on the importance of climate adaptation strategies, access to contacts with local extension officers (AEC), farming experience (FE), and farm size (FS), the results did not reveal much variation between the two categories of adoption. However, it is interesting to note that both off-farm income and farm income of farmers practicing climate adaptation strategies [Rs.26,503 (US$ 355.94) and Rs. 120,717 (US$1,621.23), respectively], were considerably higher compared to farmers not willing to practice climate adaptation strategies [Rs. 19,811 (US$266.06) and Rs. 119,900 (US$1,610.26), respectively]. Thus, it was evident that the farmers practicing climate adaptation strategies benefitted by getting higher off-farm income and farm income. On average, the respondents had 45 years of age with 13 years of FE and derived ~83% of their annual income from agriculture and the remaining 17 % from off-farm sources.

## Relative significance of the discriminating variables

Table 5 represents the summary data for the discriminant analysis, and the analysis yielded one discriminant function for two categories of climate change adaptation. The findings include both unstandardized and standardized discriminant (canonical) function coefficients, and they were meant for evaluating the relative contribution of each of the predictor variables as discriminators between two categories. When predictors were measured in different units, the magnitude of an unstandardized coefficient provides little indication of its relative contribution to the discriminant function. Hence, standardizing the coefficients was necessary, to have a common scale of measurement for comparative purposes as all the predictor variables (Kumari et al., 2017).

In the derived function, the sign indicates the direction of the relationship, and the magnitude indicates the extent of contribution to the group discrimination. It is important to note that the larger the standardized coefficient (b), the larger the respective variable's unique contribution to the group discrimination (irrespective of the sign of the coefficient). All the predictors except TRG were positively influencing the discrimination of groups. It was further apparent from the analysis that off-farm income (b5 = 0.658), farm income (b7 = 0.558), and farming experience (b1 = 0.517) were the highest discriminating variables with the largest contributions. This implies that appropriate attention should be given to promoting off-farm employment opportunities. Furthermore, the farming experience should be considered in practicing/implementing climate change adaptation strategies. Therefore, by using the variables and the standardized coefficients, the required discriminant equation (discriminator) is shown as follows:

$$\begin{aligned} Z = {} & 0.517\mathrm{FE} - 0.085\mathrm{TRG} + 0.219\mathrm{AGE} + 0.122\mathrm{EC} \\ & + 0.658\mathrm{OFFI} + 0.112\mathrm{FS} + 0.558\mathrm{FI} \end{aligned} \tag{3}$$

The classification results (Table 6) reveal that 79 % of respondents were classified correctly into "Willing" or "Non-willing" groups, and this overall predictive accuracy of the discriminant function represents the "hit ratio" (based on cross-validated set of data). Farmers willing to tackle climate change were classified with slightly better accuracy (84.1%) than their counterparts (74.7%).

### Structure matrix

In addition to standardized coefficients, the structural matrix was also employed (Table 7) to check the relative importance of the predictors. This provides another way to study the usefulness of each predictor variable in the discriminant function. This indicates the product–moment correlations between the discriminating variables and discriminant function. Factor loadings of ≥0.30 were used as the cutoff between important and less important variables, that is, if the structure coefficient was ≥0.30, it was considered meaningful (Duong et al., 2017; Halagundegowda et al., 2017; Kumari et al., 2017). The findings indicated that the structure coefficients with the highest relationship to function 1 were OFFI (0.846), FI (0.789), and FE (0.730). These three predictors had a positive correlation with the function. Squaring the coefficient of a predictor will explain the proportion of variation in the dependent variable. For instance, OFFI can explain 72% ($=0.846^2$) variation in the dependent variable. With 0.30 as the cutoff point, the other predictors, viz., TRG, AGE, AEC, and FS, were not loaded on the discriminant function, that is, these predictors are, therefore, not significantly associated with climate

TABLE 4 Descriptive statistics (Group means) across selected categories of farmers.

| Adoption of CCAS | Pooled | | Adopters | | Non-adopters | |
|---|---|---|---|---|---|---|
| | Mean | S. D | Mean | S. D | Mean | S. D |
| Farming experience | 12.66 | 3.04 | 13.2 | 2.89 | 11.69 | 3.08 |
| Training on climate change adaptation strategies | 0.54 | 0.5 | 0.56 | 0.5 | 0.52 | 0.5 |
| Age of the farmer | 44.76 | 8.01 | 45.08 | 7.97 | 44.19 | 8.09 |
| Access to extension contacts | 0.13 | 0.38 | 0.14 | 0.41 | 0.13 | 0.33 |
| Off-farm income | 24,093 | 11,756 | 26,503 | 11,843 | 19,810 | 10,325 |
| Farm size | 3.5 | 2.47 | 3.55 | 2.5 | 3.42 | 2.43 |
| Farm income | 120,423 | 13,158 | 120,717 | 12,844 | 119,900 | 13,729 |

TABLE 5 Summary of unstandardized and standardized canonical discriminant function coefficients.

| Variables | Unstandardized coefficients | Standardized coefficients |
|---|---|---|
| | Function 1 | Function 1 |
| Intercept | −5.680 | |
| Farming experience | 0.175 | 0.517 |
| Training | −0.170 | −0.085 |
| Age | 0.027 | 0.219 |
| Access to climate information | 0.319 | 0.122 |
| Off-farm income | 0.000 | 0.658 |
| Farm size | 0.045 | 0.112 |
| Farm income | 0.000 | 0.558 |

TABLE 6 Classification of results for the discriminant function.

| | | CCAS | Predicted group membership | | Total |
|---|---|---|---|---|---|
| | | | 0.00 | 1.00 | |
| Original | Count | 0 | 82 | 17 | 99 |
| | | 1 | 42 | 259 | 301 |
| | % | 0 | 82.8 | 17.2 | 100 |
| | | 1 | 13.9 | 86.1 | 100 |
| Cross-validated | Count | 0 | 74 | 25 | 99 |
| | | 1 | 48 | 253 | 301 |
| | % | 0 | 74.7 | 25.3 | 100 |
| | | 1 | 15.9 | 84.1 | 100 |

TABLE 7 Structure matrix.

| Predictor | Function 1 |
|---|---|
| FE | 0.730** |
| TRG | −0.123 |
| AGE | 0.158 |
| AEC | 0.044 |
| OFFI | 0.846** |
| FS | 0.071 |
| FI | 0.789** |

**Significant at 1% level.

TABLE 8 Functions at group centroids.

| CCAS | Function 1 |
|---|---|
| 0.00 | −0.447 |
| 1.00 | 0.252 |

change adaptation strategies. AEC was the weakest predictor and suggests that it was not associated with adaptation strategies but a function of other unassessed factors.

The group centroids were the averages of Z-values calculated by the estimated model, which can be used to evaluate the expected position of the concerned farmers' categories (Uddin et al., 2013). As can be seen in Table 8, the centroid of the non-willing category was −0.447, and the centroid of the "willing" category was 0.252. This implies that if someone's score on the discriminant function was positive (closer to 0.252), then that respondent was probably willing to tackle climate change. On the contrary, if a person's score on the discriminant function was negative (closer to −0.447), then the data probably came from the "non-willing" category. On calculating the cut score (halfway between the two centroids), that is, −0.097 and if a person's score on the discriminant function (calculated by plugging in their scores on predictor variables) was above −0.097, then the respondent was probably from the "willing" category. On the contrary, if the discriminant function score was below −0.097, then the respondent was probably from the "non-willing" category.

Finally, the performance of the model was studied using the receiver operating characteristic (ROC) curve to compare sensitivity vs. specificity across a range of values for the ability to predict a dichotomous outcome. The area under the ROC curve was another measure of test performance (Figure 3). The results showed a large area under the curve (AUC) of 71.4%, significant at the 5% level, which further affirmed that the model was correctly specified.

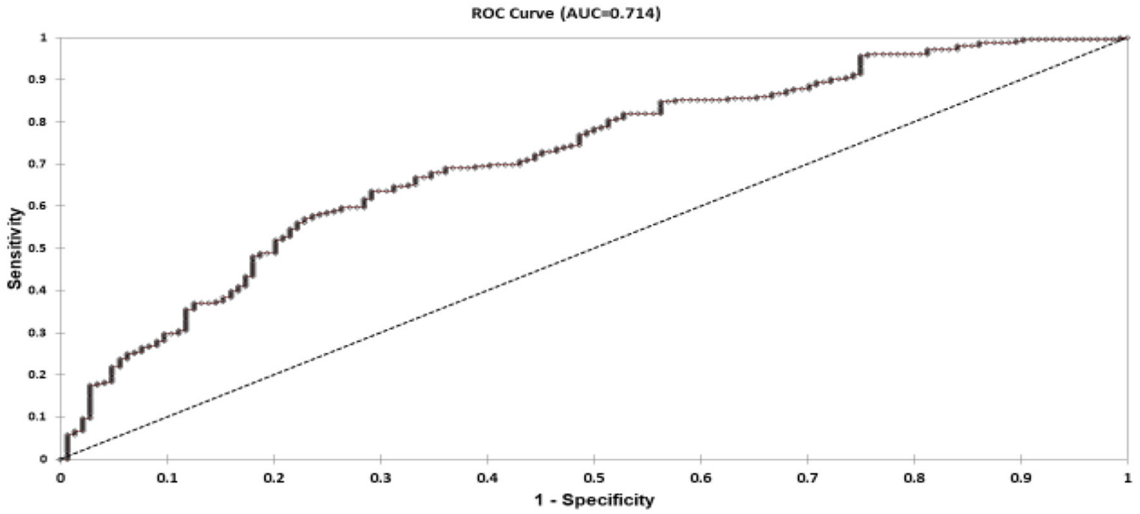


FIGURE 3
Receiver operating characteristic (ROC) curve.

### Determinants for climate change adaptation strategies

The findings of the multinomial logistic model (Table 9) revealed that farming experience, farm income, access to climate information, and education (at 1% level) and off-farm income and Access to market (at 5% level) were significantly influencing the farmers to practice crop diversification toward less-water consuming and drought-resistant crops. For integrating crops with livestock, farming experience, farm income, access to market, livestock ownership (at 1% level) access to extension contacts, and farm size (at 5% level) were the most significant factors. Change in planting date was significantly influenced by farming experience, farm income, access to climate information (at 1% level), and training and education (at 5% level). Regarding the adoption of soil and water conservation practices, it was significantly influenced by farming experience, off-farm income, farm income, and access to climate information (at 1% level) and education (at 5% level). A close perusal of the table further revealed that farming experience and farm income were the crucial factors that promote the farmers to take up the climate change adaptation strategies in the southern states. The marginal effects of farming experience indicated that, for every 1-year increase, the probabilities of practicing crop diversification, integrating crops with livestock, changing planting dates, and adopting soil and water conservation practices were increased by 1.06, 0.03, 1.83, and 1.48%, respectively. Similarly, the marginal effects of farm income indicated that a unit increase in income could increase the likelihood of practicing crop diversification, integrating crops with livestock, changing planting dates, and adopting soil and water conservation practices by 9.15, 8.51, 9.33, and 4.13%, respectively. Access to climate information is another important variable that contributed to the adaptation options among the selected farmers. As expected, the findings showed that the farmers' access to climate change information had affected the likelihood of adaptation to climate change by practicing crop diversification (1.47%), change in planting date (2.36%), and adoption of soil and water conservation practices (1.17%). This implies that the farmers who enjoy better access to climate change information (i.e., seasonal or mid-term forecasting) made better-informed adaptation decisions. These findings were similar to the findings from various studies (Belay et al., 2017; Halagundegowda et al., 2017; Adeagbo et al., 2021; Tshikororo et al., 2021). As expected by the researchers, education and livestock rearing had a positive association across all climate change adaptation strategies. Other determinants like access to market (on crop diversification −1.61% and integrating crop with livestock 1.84%), farm size (on integrating crop with livestock −2.67%), and training (on change in planting date −3.02%) have exerted a significant positive influence on the adoption of climate change adaptation strategies.

## Conclusion and policy implications

Climate change is one of the biggest challenges to agriculture, particularly for smallholder farming in developing countries like India. Therefore, it is inevitable for the farmers to plan and resort to different climate change adaptation strategies to stabilize and diversify agricultural production and augment farm income on a sustainable basis. The variables such as off-farm income, farm income, and farming experience emerged as determining factors to adopt CCAS. Thus, policy efforts on these significant variables are to be given high priority to motivate the farmers for practicing climate change adaptation strategies and to instill confidence among the farmers in farming. Moreover, creating off-farm employment/income opportunities for the farmers deserve special attention through rural non-farm activities, which are less sensitive to climate change. The policy implications that emerge from this study are as follows: The role of institutions is crucial in the capacity building of smallholders to safeguard their interests through a wide range of policy, research, and technological interventions. Aspects such as crop diversification, linking farmers to agricultural markets, improving access to climate change information, application of ICTs and artificial intelligence in information dissemination, and knowledge about various climate change adaptation strategies (long-term drought-proofing measures) should be included in the current formal agricultural extension system in the country inculcate spirit in the farming community. In a nutshell, R&D focus on climate-resilient agriculture as well as

**TABLE 9** Parameter estimates of multinomial logistic model for CCAS by sample farmers.

| Variable | Crop diversification ($n_1 = 63$) | | Integrating crop with livestock ($n_2 = 51$) | | Change in planting date ($n_3 = 87$) | | Adoption of soil water and conservation practices ($n_4 = 55$) | |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | Marginal effect ($\partial Y_j/\partial X_{ij}$) | Coefficient | Marginal effect ($\partial Y_j/\partial X_{ij}$) | Coefficient | Marginal effect ($\partial Y_j/\partial X_{ij}$) | Coefficient | Marginal effect ($\partial Y_j/\partial X_{ij}$) |
| Farming experience (FE) | 0.1015 (0.0432) | 0.0106** (0.0025) | 0.0708 (0.0264) | 0.0026** (0.0008) | 0.1136 (0.0632) | 0.0183** (0.0071) | 0.0277 (0.0019) | 0.0148** (0.0039) |
| Training (TRG) | 0.2828 (0.0167) | 0.0372 (0.0261) | 0.1432 (0.1305) | 0.0126 (0.04327) | 0.3357 (0.1408) | 0.0302* (0.0125) | 0.3624 (0.4956) | 0.0246 (0.0023) |
| Age (AGE) | −0.1158 (0.1019) | −0.0052 (0.0033) | −0.1747 (0.1238) | −0.0168 (0.0031) | −0.1499 (0.0261) | −0.0082 (0.0067) | 0.1441 (0.0966) | 0.0024 (0.0015) |
| Access to extension contacts (AEC) | 0.8211 (0.4019) | 0.0978 (0.0522) | 0.4985 (0.1957) | 0.0156* (0.0135) | 0.6735 (0.2878) | 0.0371 (0.0197) | 0.3458 (0.1266) | 0.0138 (0.0126) |
| Off–farm income (OFFI) | 0.0013 (0.0005) | 0.0676* (0.0281) | −0.0516 (0.0412) | −0.0152 (0.0458) | 0.0000177 (0.000016) | 0.0016 (0.0038) | 0.0239 (0.0016) | 0.0689** (0.0251) |
| Farm size (FS) | 0.0519 (0.0597) | 0.0068 (0.0095) | 0.0272 (0.0032) | 0.0267* (0.0115) | 0.0033 (0.0011) | 0.0341 (0.0279) | −0.1334 (0.0977) | −0.0053 (0.0042) |
| Farm income (FI) | 4.9312 (1.9678) | 0.0915** (0.0017) | 0.0016 (0.0001) | 0.0851** (0.0167) | 0.0321 (0.0012) | 0.09327** (0.0052) | 0.0164 (0.0053) | 0.0413** (0.0012) |
| Access to climate information (AC) | 0.0129 (0.0028) | 0.0147** (0.0046) | 0.3119 (0.3561) | 0.0053 (0.0465) | 0.1073 (0.0135) | 0.0236** (0.0064) | 0.0816 (0.0279) | 0.0117** (0.0024) |
| Access to market (AM) | 0.0799 (0.0366) | 0.0161* (0.0072) | 0.1411 (0.0288) | 0.0184** (0.0071) | −0.2388 (0.4219) | −0.0288 (0.0511) | 0.8454 (0.8011) | 0.0343 (0.0219) |
| Education (EDU) | 0.0159 (0.0016) | 0.0275** (0.0099) | −0.0428 (0.0657) | −0.0059 (0.0093) | 0.0335 (0.0142) | 0.0028* (0.0012) | 0.0933 (0.0423) | 0.0138* (0.0059) |
| Livestock ownership (LO) | 0.4141 (0.3761) | 0.0854 (0.0663) | 0.1998 (0.0441) | 0.0569* (0.0053) | 0.2774 (0.4957) | 0.0496 (0.0447) | 0.9334 (0.5721) | 0.0549 (0.0408) |
| Constant | 4.8531 (1.9621) | | 10.5932 (2.0886) | | 6.5866 (2.2876) | | 6.303853 (3.23769) | |

**Significant at 1% level, *significant at 5% level.

promoting the development of the non-farm sector in rural areas is crucial to sustaining their livelihoods as these serve as potential mitigation strategies to impart resilience to climate-sensitive sectors like agriculture, and water in rainfed regions of the country.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

KK, MR, and KR conceived the study, sourced and analyzed the data, and wrote the draft manuscript. VP, MB, TK, RK, and DR validated the results, edited the draft, and improved the content. All authors approved the final draft.

## Acknowledgments

We thank the financial support provided by ANGRAU, Bapatla, Andhra Pradesh, and PJTSAU, Telangana. The authors are also thankful to ICAR–Central Tobacco Research Institute, Rajahmundry, Andhra Pradesh, and ICAR–Central Coastal Agricultural Research Institute, Old Goa, Goa, India, for providing the necessary facility.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor RG declared a past co-authorship with one of the authors KR.

## Publisher's note

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1010527/full#supplementary-material

## References

Abdulai, A., and Huffman, W. (2014). The adoption and impact of soil and water conservation technology: an endogenous switching regression application. *Land Econ.* 90, 26–43. doi: 10.3368/le.90.1.26

Adeagbo, O. A., Ojo, T. O., and Adetoro, A. A. (2021). Understanding the determinants of climate change adaptation strategies among smallholder maize farmers in South-West, Nigeria. *Heliyon* 7, e06231. doi: 10.1016/j.heliyon.2021.e06231

Agrawala, S., and Lemos, M. C. (2015). Adaptive development. *Nat. Clim. Change* 5, 185–187. doi: 10.1038/nclimate2501

Almaraz, J. J., Mabood, F., Zhou, A., Gregorich, E. G., and Smith, D. L. (2008). Climate change, weather variability and corn yield at a higher latitude locale: south-western Quebec. *Clim. Change* 88, 187–197. doi: 10.1007/s10584-008-9408-y

Anik, A. R., Rahman, S., Sarker, J. R., and Al Hasan, M. (2021). Farmers' adaptation strategies to combat climate change in drought prone areas in Bangladesh. *Int. J. Disaster Risk Reduct.* 65, 102562. doi: 10.1016/j.ijdrr.2021.102562

Aryal, J. P., Sapkota, T. B., Rahut, D. B., Marenya, P., and Stirling, C. M. (2021), Climate risks and adaptation strategies of farmers in East Africa and South Asia. *Sci. Rep.* 11, 10489, doi: 10.1038/s41598-021-89391-1

Asafu-Adjaye, J. (2008), Factors affecting the adoption of soil conservation measures: a case study of Fijian cane farmers. *J. Agric. Resourc. Econ.* 33.

Asrat, P., and Simane, B. (2018). Farmers' perception of climate change and adaptation strategies in the Dabus watershed, North-West Ethiopia. *Asrat Simane Ecol. Proc.* 7, 7. doi: 10.1186/s13717-018-0118-8

Auffhammer, M., and Schlenker, W. (2014), Empirical studies on agricultural impacts and adaptation. *Energy Econ.* 46, 555–561. Available online at: http://refhub.elsevier.com/S0308-521X(22)00201-3/rf0030

Barzola Iza, C. L., and Dentoni, D. (2020). How entrepreneurial orientation drives farmers' innovation differential in Ugandan coffee multi-stakeholder platforms. *J. Agribus. Dev. Emerg. Econ.* 10, 629–650. doi: 10.1108/JADEE-01-2020-0007

Belay, A., Recha, J. W., Woldeamanuel, T., and Morton, J. F. (2017). Smallholder farmers' adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. *Agric. Food Secur.* 6, 1–13. doi: 10.1186/s40066-017-0100-1

Campbell, B. M., Vermuelen, S. J., Aggarwal, P. K., Corner-Dolloff, C., Givertz, E., Loboguerrerro, A. M., et al. (2016). Reducing risks to food security from climate change. *Glob. Food Sec.* 11, 34–43. doi: 10.1016/j.gfs.2016.06.002

CIE (2014). *Analysis of the Benefits of Improved Seasonal Climate Forecasting for Agriculture, Canberra ACT 2609.* The Centre for International Economics.

Connoly-Boutin, L. C., and Smit, B. (2015). Climate change, food security, and livelihood in Sub-Saharan Africa. *Reg. Environ. Change* 16, 385–399. doi: 10.1007/s10113-015-0761-x

Croppenstedt, A., Knowles, M., and Lowder, S. (2018). Social protection and agriculture: introduction to the special issue. *Glob. Food Sec.* 16, 65–68. doi: 10.1016/j.gfs.2017.09.006

Das, H. P. (2005). "Agro meteorological impact assessment of natural disasters and extreme events and agricultural strategies adopted in areas with high weather risk," in: *Natural Disaster and Extreme Events in Agriculture,* eds M. V. K. Shivakumar,, P. R. Motha, H. P. Das (Berlin; New York, NY: Springer-Verlag), 93–118. doi: 10.1007/3-540-28307-2_6

Diallo, A., Donkor, E., and Owusu, V. (2020). Climate change adaptation strategies, productivity and sustainable food security in southern Mali. *Clim. Change* 159, 309–327. doi: 10.1007/s10584-020-02684-8

Duong, N. T., Ha, D. T. T., and Ngoc, N. B. (2017). The application of discriminant model in managing credit risk for consumer loans in Vietnamese commercial bank. *Asian Soc. Sci.* 13, 176–186. doi: 10.5539/ass.v13n2p176

Easterling, W. E., Aggarwal, P. K., Batima, P., Brander, K. M., Erda, L., Howden, S. M., et al. (2007). Food, fibre and forest products. *Clim. Change* 273–313.

Food and Agriculture Organization. (2011). *Crop Prospects and Food Situation (no. 4, December, 2011)*. Available online at: http://www.fao.org/docrep/014/al983e/al983e00.pdf

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., et al. (2010). Implications of climate change for agricultural productivity in the early twenty-first century. *Philos. Trans. R. Soc. B Biol. Sci.* 365, 2973–2989. doi: 10.1098/rstb.2010.0158

Government of India (2017). "Climate, climate change, and agriculture," in *Economic Survey*. New Delhi: Ministry of finance, Government of India, 96–97.

Halagundegowda, G. R., Singh, A., and Meenakshi, H. K. (2017). Discriminant analysis for prediction and classification of farmers based on adoption of drought coping mechanisms. *Agric. Update* 12, 635–664. doi: 10.15740/HAS/AU/12.TECHSEAR(3)2017/635-640

IPCC (2013). *The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 1*. New York, NY: Cambridge University Press, 535–541.

IPCC. (2012). "Managing the risks of extreme events and disasters to advance climate change adaptation," in *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, eds C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. -K. Plattner, S. K. Allen, M. Tignor, and P. M. Midgley (Cambridge; New York, NY: Cambridge University Press), 1–582.

IPCC. (2014). "Climate change 2014: Mitigation of climate change," in *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds O. R. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J. C. Minx (Cambridge; New York, NY: Cambridge University Press).

Khanal, A. R., and Mishra, A. K. (2017). Enhancing food security: food crop portfolio choice in response to climatic risk in India. *Glob. Food Sec.* 12, 22–30. doi: 10.1016/j.gfs.2016.12.003

Khemakhem, S., and Boujelbene, Y. (2015).Credit risk prediction: A comparative study between discriminant analysis and the neural network approach. Account. *Manag. Inform. Syst.* 14, 1–60.

Kibue, G. W., Liu, X., Zheng, J., Pan, G., Li, L., and Han, X. (2016). Farmers' perceptions of climate variability and factors influencing adaptation: evidence from Anhui and Jiangsu, China. *Environ. Manage.* 57, 976–986. doi: 10.1007/s00267-016-0661-y

Kosoe, E. A., and Ahmed, A. (2022), Climate change adaptation strategies of cocoa farmers in the Wassa East District: implications for climate services in Ghana. *Clim. Serv.* 26, 100289. doi: 10.1016/j.cliser.2022.100289

Kumari, M., Singh, K. M., Mishra, R. R., Sinha, D. K., and Ahmad, N. (2017). Role of socio-economic variables in adoption of crop insurance: a discriminant function approach. *Econ. Affairs* 62, 361–365. doi: 10.5958/0976-4666.2017.00045.6

Lobell, D. B., Schlenker, W., and Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science.* 333, 616–620. doi: 10.1126/science.1204531

Lotze-Campen, H., and Schellnhuber, H. J. (2009). Climate impacts and adaptation options in agriculture: what we know and what we don't know. *J. Verbr. Lebensm.* 4, 145–150. doi: 10.1007/s00003-009-0473-6

Malek, K., Adam, J. C., Stöckle, C. O., and Peters, R. T. (2018). Climate change reduces water availability for agriculture by decreasing non evaporative irrigation losses. *J. Hydrol.* 561, 444–460.

Mendelsohn, R., Basist, A., Kurukulasuriya, P., and Dinar, A. (2006). Climate change and rural income. *Clim. Change* 81, 101–118. doi: 10.1007/s10584-005-9010-5

Misra, A. K. (2012). Climate change impacts, mitigation and adaptation strategies for agricultural and water resources, in Ganga plain (India). *Mitigat. Adapt. Strat. Glob. Change* 18, 673–689. doi: 10.1007/s11027-012-9381-7

Misra, A. K. (2014). Climate change and challenges of water and food security. *Int. J. Sustain. Built Environ.* 3, 153–165. doi: 10.1016/j.ijsbe.2014.04.006

Mjelde, J. W., Sonka, S. T., and Pell, D. S. (1989). *The Socioeconomic Value of Climate and Weather Forecasting: A Review*. Midwestern Climate Center, Climate & Meteorology Section Illinois State Water Survey.

Motha, R. P., and Murthy, V. R. K. (2007). "Agrometeorological services to cope with risks and uncertainties," in *Managing Weather and Climate Risks in Agriculture*, eds V. K. Sivakumar and R. P. Motha (Berlin; Heidelberg: Springer), 435–462.

Mulwa, C., Marenya, P., and Kassie, M. (2017). Response to climate risks among smallholder farmers in Malawi: a multivariate probit assessment of the role of information, household demographics, and farm characteristics. *Clim. Risk Manag.* 16, 208–221. doi: 10.1016/j.crm.2017.01.002

Mushore, T. D., Mhizha, T., Manjowe, M., Mashawi, L., Matandirotya, E., Mashonjowa, E., et al. (2021). Climate change adaptation and mitigation strategies for small holder farmers: a case of Nyanga District in Zimbabwe. *Front. Clim.* 3, 676495. doi: 10.3389/fclim.2021.676495

Mwinkom, F. X., Damnyag, L., Abugre, S., and Alhassan, S. I. (2021), Factors influencing climate change adaptation strategies in North-Western Ghana: evidence of farmers in the Black Volta Basin in Upper West region. *SN Appl. Sci.* 3, 548. doi: 10.1007/s42452-021-04503-w

Nabikilo, D., Bashaasha, B., Mangheni, M. N., and Majaliwa, J. G. M. (2012). Determinants of climate change adaptation among male and female headed farm households in Eastern Uganda. *Afr. Crop. Sci. J.* 20, 203–212.

Narain, S., Ghosh, P., Saxena, N., Parikh, J., and Soni, P. (2009). *Climate Change—Perspectives From India*. United Nations Development Programme (UNDP).

Ndamani, F., and Watanabe, T. (2016). Determinants of farmers' adaptation to climate change: A micro level analysis in Ghana. *Agrometeorol. Sci. Agric.* 73, 201–208. doi: 10.1590/0103-9016-2015-0163

Nelson, G. C., Rosegrant, M. W., Koo, J., Robertson, R., Sulser, T., Zhu, T., et al. (2009). *Climate Change: Impact on Agriculture and Costs of Adaptation*. Washington, DC: International Food Policy Research Institute–IFPRI.

Niles, M. T., Brown, M., and Dynes, R. (2016). Farmer's intended and actual adoption of climate change mitigation and adaptation strategies. *Clim. Change* 135, 277–295. doi: 10.1007/s10584-015-1558-0

Ogen, O. (2007). *The Agricultural Sector and Nigeria's Development: Comparative Perspectives From the Brazilian Agro-industrial Economy*. Nebula, 1960–1995.

Ojo, T. O., and Baiyegunhi, L. J. S. (2019). Determinants of climate change adaptation strategies and its impact on the net farm income of rice farmers in south-west Nigeria. *Land Use Policy* 95, 103946. doi: 10.1016/j.landusepol.2019.04.007

Pino, G., Toma, P., Rizzo, C., Miglietta, P., Peluso, A., and Guido, G. (2017). Determinants of farmers' intention to adopt water saving measures: evidence from Italy. *Sustainability* 9, 77. doi: 10.3390/su9010077

Piya, L., Maharjan, K. L., and Joshi, N. J. (2013). Determinants of adaptation practices to climate change by chepang households in the rural mid-Hills of Nepal. *Reg. Environ. Change* 13, 437–447. doi: 10.1007/s10113-012-0359-5

Reidsma, P., Ewert, F., Lansink, A. O., and Leemans, R. (2009). Vulnerability and adaptation of European farmers: a multi-level analysis of yield and income responses to climate variability. *Reg. Environ. Change* 9, 25–40. doi: 10.1007/s10113-008-0059-3

Rosenzweig, C., and Tubiello, F. N. (2007). Adaptation and mitigation in agriculture: an analysis of potential synergies. *Mitig. Adapt. Strat. Glob. Change* 12, 855–873. doi: 10.1007/s11027-007-9103-8

Shrestha, S., and Bui, T. T. T. (2015). Assessment of climate change impacts and evaluation of adaptation measures for paddy productivity in Quangnam province, Vietnam. *Paddy Water Environ.* 13, 241–253. doi: 10.1007/s10333-014-0434-2

Shrestha, U. B., Gautam, S. and Bawa, K. S. (2012). Widespread climate change in the Himalayas and associated changes in local ecosystems. *PLoS ONE.* 7, 36741. doi: 10.1371/journal.pone.0036741

Singh, N. P., Anand, B., Singh, S., and Khan, A. (2019). Mainstreaming climate adaptation in Indian rural developmental agenda: a micro-macro convergence. *Clim. Risk Manage.* 24, 30–41. doi: 10.1016/j.crm.2019.04.003

Sivakumar, M. V. K. (2011). "Operational agro meteorological strategies in different regions of the world," in *Challenges and Opportunities in Agrometeorology*, eds S. D. Attri, L. S. Rathore, M. V. K. Sivakuma, and S. K. Dash, editors (Berlin; New York, NY: Springer-Verlag), 551–571. doi: 10.1007/978-3-642-19360-6_43

St Clair, S. B., and Lynch, J. P. (2010). The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. *Plant Soil.* 35, 101–115.

Tang, X., Li, J., Ma, Y., Hao, X., and Li, X. (2008). Phosphorus efficiency in long-term (15 years) wheat-maize cropping systems with various soil and climate conditions. *Field Crops Res.* 108, 231–237. doi: 10.1016/j.fcr.2008.05.007

Tesfahunegn, G., Mekonen, K., and Tekle, A. (2016). Farmers' perception on causes, indicators and determinants of climate change in northern Ethiopia: implication for developing adaptation strategies. *Appl. Geogr.* 73, 1–12. doi: 10.1016/j.apgeog.2016.05.009

Tshikororo, M., Thaba, K., Nefale, T. A., and Tshikororo, M. (2021). Perception driven from farmers' socio-economic characteristics towards tackling climate change. *J. Agric. Sci.* 13, 41–47. doi: 10.5539/jas.v13n6p41

Turpie, J., and Visser, M. (2013). The impact of climate change on South Africa's rural areas. *Fin. Fiscal Comm.* 14, 100–160.

Uddin, M. S., Shah, M. A. R., Khanom, S., and Nesha, M. K. (2013). Climate change impacts on the Sundarbans mangrove ecosystem services and dependent livelihoods in Bangladesh. *Asian J. Conserv. Biol.* 2, 152-156. Available online at: https://www.ajcb.in/journals/full_papers_dec_2013/AJCB-Vol2-No2-Shams-Uddin%20et%20al.pdf

Verchot, L. V., Noordwijk, M. V., Kandji, S., Tomich, T., Ong, C., Albrecht, A., et al. (2007). Climate change: linking adaptation and mitigation through agroforestry. *Mitigat. Adapt. Strateg. Glob. Chang.* 12, 901–918.

Von Braun, J., Swaminathan, M. S., and Rosegrant, M. W. (2005). *Agriculture, Food Security, Nutrition and the Millennium Development Goals*. International Food Policy Research Institute.

Yamane, T. (1967). *Statistics: An Introductory Analysis. 2nd Edn.* New York, NY: Harper and Row.

Zizinga, A., Kangalawe, R. Y. M., Ainslie, A., Tenywa, M. M., Majaliwa, J., Saronga, N. J., et al. (2017). Analysis of farmer's choices for climate change adaptation practices in South-Western Uganda, 1980–2009. *Climate.* 89, 1–15.

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 08 March 2023
DOI 10.3389/fsufs.2023.1078314

EDITED BY
Subhasis Mandal,
Central Soil Salinity Research Institute (ICAR), India

REVIEWED BY
Abdullah-Al Mamun,
Noakhali Science and Technology University, Bangladesh
M. Krishnan,
Indian Council of Agricultural Research (ICAR), India
Krishnan Pandian,
Bay of Bengal Programme Inter Governmental Organisation, India

*CORRESPONDENCE
Shinoj Parappurathu
✉ pshinoj@gmail.com

SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 24 October 2022
ACCEPTED 16 February 2023
PUBLISHED 08 March 2023

CITATION
Parappurathu S, Menon M, Jeeva C, Belevendran J, Anirudhan A, Lekshmi PSS, Ramachandran C, Padua S, Aswathy N, Ghosh S, Damodaran D, Megarajan S, Rajamanickam G, Vinuja SV, Ignatius B, Raghavan SV, Narayanakumar R, Gopalakrishnan A and Chand P (2023) Sustainable intensification of small-scale mariculture systems: Farm-level insights from the coastal regions of India. *Front. Sustain. Food Syst.* 7:1078314. doi: 10.3389/fsufs.2023.1078314

# Sustainable intensification of small-scale mariculture systems: Farm-level insights from the coastal regions of India

Shinoj Parappurathu[1]*, Muktha Menon[1], Charles Jeeva[1], Johnson Belevendran[1], Anuraj Anirudhan[1], P. S. Swathi Lekshmi[1], C. Ramachandran[1], Shelton Padua[1], Natarajan Aswathy[1], Shubhadeep Ghosh[1], Divu Damodaran[1], Sekar Megarajan[1], Geetha Rajamanickam[2], S. V. Vinuja[1], Boby Ignatius[1], Suresh Vettath Raghavan[1], Ramani Narayanakumar[1], Achamveetil Gopalakrishnan[1] and Prem Chand[3]

[1]ICAR-Central Marine Fisheries Research Institute (CMFRI), Kochi, India, [2]ICAR-Central Institute of Brackishwater Aquaculture (CIBA), Chennai, India, [3]ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi, India

This study undertakes a comprehensive assessment of selected mariculture enterprises in the coastal regions of India, centered on long-term sustainability as the key focus. This is juxtaposed against India's ambitious blue economy targets and policy thrust that pin on the expansion of mariculture as a promising avenue for enhancing marine fish production. Farm-level, region-specific, techno-economic, and socio-cultural factors associated with, and conditional on, sustainable intensification of mariculture-based production systems are examined in detail. The Principles-Criteria-Indicators (PCI) approach is used to establish the linkage between identified farm-level indicators and various dimensions of sustainability. While the selected enterprises were assessed to be technically and economically viable in general, glaring gaps were evident on key indicators of sustainability such as the legitimacy of access over water bodies, use of quality seed and feed, institutional credit access, market access, and fair marketing practices, optimal stocking density, mechanization, use of renewable energy, adoption of environmental-friendly culture practices, farm surveillance, crew safety, and social protection. This indicates the need for taking proactive measures to ensure the long-term sustainability of mariculture, particularly in the initial stages of establishment when such interventions are easy to adopt. Based on the insights obtained from the analysis, a broad set of strategies, policy options, and institutional interventions critical to scaling-up coastal mariculture enterprises along the east and west coasts of India are presented.

KEYWORDS

**mariculture, cage culture, small-holder aquaculture, sustainable intensification, diversified coastal economy, production system assessment, blue economy, India**

## 1. Introduction

The significance of the "blue economy" as a paradigm toward furthering sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem has been widely accepted [(World Bank and United Nations Department of Economic and Social Affairs (UN-DESA), 2017)]. Capture fisheries, finfish, and bivalve mariculture constitute the main food-producing sectors in the ocean. They form the key components of the blue economy and account for about 17 percent of global edible meat production (Costello et al., 2020). Recent studies have indicated that, through the intensification of mariculture,[1] aided by commensurate technological improvements and policy reforms, it is possible to enhance food from the sea by 21–44 million tons (36–74% increase compared to current yields) by 2050 (Edwards et al., 2019; Costello et al., 2020). There are already sufficient indications to suggest that commercial farming of marine fish and shellfish species, mainly those with high export demand, will take off at unprecedented levels across the globe. For instance, farming Atlantic salmon off Norway's coast has become a global business that generates US$ 18 billion in annual revenue. This industry operates at such high levels of economies of scale that offshore marine cages at Norwegian salmon farms often have a circumference of up to 157 m, enclosing water volume of ∼40,000 $m^3$, and hold up to 200,000 individual fish, wherein each farming crew is responsible for several million animals, amounting to the biomass of up to 15,000 tons (Fore et al., 2018). Similar accounts of success have been reported from other countries such as China, Chile, the United States, and Ireland, where mariculture has been established as a commercial industry. Technological breakthroughs in breeding for disease resistance and other traits using genetic and genomic interventions, which enable farmed fish species to grow roughly twice as fast as their wild counterparts, have made such remarkable success possible (Stockstad, 2020). Precision fish farming (PFF) techniques that help maneuver environmental parameters for optimal growth are catalyzing the transition (Fore et al., 2018; Wang et al., 2021). Besides, recent assessments of biological production potential for mariculture, despite being subject to substantial constraints based on existing ocean uses, indicate the availability of vast swathes of ocean space in nearly every coastal country which are suitable for future development (Gentry et al., 2017; Troell et al., 2017; Clawson et al., 2022).

Nevertheless, ensuring holistic sustainability in the pursuit of large-scale mariculture production enhancement, mainly when driven by commercial interests, is easier said than done. Previous experiences in the commercial expansion of the shrimp aquaculture industry around the world during the 1990s are ample testimony to the far-reaching negative economic externalities of expansionist policies that are unmindful of sustainability (Primavera, 1997; Arquitt et al., 2005; Belton and Little, 2008; Davies et al., 2019; Salunke et al., 2020). Such concerns are equally applicable in mariculture as well, and therefore, the global discourse on the prospects of mariculture as a sustainable food production industry continues to remain contested. Against the worldwide euphoria driven by a recent wave of literature that promotes mariculture as a "technological and spatial fix" for apparent constraints to terrestrial food production, some studies warn of the potential adverse impacts that touch upon environmental, economic, and social dimensions of sustainability. Belton et al. (2020) note that much of the literature that projects the future mariculture potential is empirically contestable, and, neglects the potential chances of appropriation of ocean space to benefit extractive industries and conservation interests through the extension of private property rights. Though broadly optimistic about the future promises of marine aquaculture, Gentry et al. (2017) stressed that future intensification in mariculture systems would be conditional upon several market and governance-related factors. Such concerns are even more relevant in developing coastal economies where a large contingent of small-scale fishers depend on marine fisheries for their livelihood. Significant capital investments for mariculture development as part of "blue economy" and "blue growth" narratives without due concern for sustainability, equity; small scale fishers' access rights, and participation could possibly jeopardize economic stability in coastal regions (Bavinck et al., 2017; Cohen et al., 2019). Moreover, the technical, logistical, and market-related pre-conditions necessary to backstop mariculture in its initial development phases are of particular relevance.

Mariculture along the shallow marine, and internal waters[2] has been a priority for fisheries development in India over the last decade. India's *National Policy on Marine Fisheries, 2017* states that mariculture can play an essential role in increasing fish production from marine and coastal waters and that the Government of India will support addressing the institutional and commercial needs of this emerging sector [(Government of India (GoI), 2017)]. Presently, mariculture is predominantly small-holder-centric in India. With steady technological advancements and faster adoption among the small-scale fisher community, supposedly, there is potential for sustainable intensification (SI) of farming operations in India's coastal regions. Some promising enterprises for possible scale-up include open sea and 'coastal water[3]' cage farming of fin fishes and shell fishes, seaweed farming, and integrated multi-trophic aquaculture (IMTA), among others (Gopalakrishnan et al., 2017; Parappurathu et al., 2017). The Government of India has recently floated ambitious programs to support such farming ventures, intending to provide the necessary logistics, funding, and policy support [(National Fisheries Development Board (NFDB), 2018)]. However, the success of such

---

[1] Mariculture or marine farming is a specialized branch of aquaculture involving the cultivation of marine organisms for food and other animal products, in enclosed sections of the open ocean (offshore mariculture), fish farms built on near-shore waters (inshore mariculture), or in artificial tanks, ponds or raceways which are filled with seawater (onshore mariculture).

[2] As per United Nations Convention on the Law of the Sea (UNCLOS), internal waters are "those waters which lie landward of the baseline from which the territorial sea is measured." This include (i) parts of the sea along the coast down to the low water mark, (ii) ports and harbours, (iii) estuaries and landward waters from the closing line of bays, and (v) waters enclosed by straight baselines.

[3] The term "Coastal water" farming is used in this paper to refer to fish farming operations carried out in internal water areas.

programs depends to a large extent on a clear understanding of the suitability of each of the above aquaculture technologies to match the specific socio-economic and demographic features of the farming community involved and the general status of the markets and institutions in the region of interest. Notably, the quality of resource endowments, entrepreneurial readiness and capital availability at the farm level, farming skills and technical prowess, the general willingness of farmers to embrace sustainable practices, community knowledge capital, and backward and forward linkages to the input and product markets, and value chain integration are important determinants (Bostock et al., 2010; Little et al., 2013; Buck and Langan, 2017). The emergence of new successful farm enterprises often results in significant changes in the rural economy, leading to mushrooming of several mutually complementary allied enterprises. Assimilation and integration of these economic units into the diversified coastal economy are equally important to positively change people's lives (Grealis et al., 2017; Seung and Kim, 2020).

Given the above context, this paper undertakes a comprehensive assessment of farm-centric and region-specific factors associated with, and conditional upon, sustainable intensification of selected mariculture enterprises in India. To set the stage, the following section deals with the potential of India's marine and coastal water aquaculture, and the efforts made so far to explore it. Further, a critical assessment of the techno-economic performance of selected mariculture enterprises and their level of alignment with key indicators of sustainable intensification is carried out based on primary surveys conducted across selected locations along India's east and west coasts. Besides, various constraints faced by mariculture entrepreneurs are discussed, and relevant technological and policy interventions to develop the sector are put forth.

## 2. Development of mariculture

### 2.1. Present status

The earliest known attempt at the culture of marine fish species in India was made during 1958–1959 with the farming of milkfish, *Chanos chanos* (Gopakumar et al., 2007). Subsequently, in the 1970s, farming trials were conducted to standardize the culture of green mussels (*Perna viridis*) and brown mussels (*P. indica*) using the rack method, long line method, and raft methods (Qasim et al., 1977; Appukuttan, 1980; Kuriakose, 1980). The culture of pearl oysters (*Pinctada fucata* and *P. margaritifera*) was also attempted along the coasts of Tamil Nadu (Alagarswami, 1974). Other budding attempts toward mariculture include seaweed culture experiments initiated for the first time in Gujarat in 1964 (Thivy, 1964), followed by farming trials and commercial exploitation along the southeast coast of Tamil Nadu for agar and algin production (Silas and Kalimuthu, 1987). Presently, mariculture in India constitutes capture and hatchery-based fin-fish and shell-fish culture, which include cage culture (in the open sea and internal waters), bivalve culture; aquaculture systems such as seaweed culture, pearl, and oyster culture, as well as ornamental fish culture. Nevertheless, the current mariculture production in India is negligible at <0.1 million tons (mt) in relation to the projected potential of 4–8 mt (Jena et al., 2022). A brief account of the status of mariculture enterprises such as cage farming, seaweed farming, and IMTA in India, which constitute key focus areas of this paper, is provided below.

Attempts on open sea cage culture were initiated in the mid-2000s with Asian sea bass (*Lates calcarifer*), which led to locally adapted innovations in the designing and fabrication of cages and mooring systems, standardized guidelines and farming practices, as well as the development of breeding, larval production, and grow-out technologies for several prioritized marine fin fish species (Rao et al., 2013; Ayyappan et al., 2015). So far, the ICAR-Central Marine Fisheries Research Institute (CMFRI), India, has standardized techniques for breeding and seed production, including nursery protocols for Cobia (*Rachycentron canadum*), Orange-spotted grouper (*Epinephelus coioides*), Silver pompano (*Trachinotus blochii*), Indian pompano (*T. mookalee*), Pink-ear sea bream (*Lethrinus lentjan*), banded grunter (*Pomadasys furcatus*), John's snapper (*Lutjanus johnii*), Vermiculated spine foot (*Siganus vermiculatus*) and picnic seabream (*Acanthopagrus berda*) (Gopalakrishnan et al., 2019; Anuraj et al., 2021; Suresh Babu et al., 2022). The culture technology for Asian Seabass was standardized by the ICAR-Central Institute of Brackishwater Aquaculture (CIBA) (Arasu et al., 2009). Apart from the above, a recent publication from ICAR-CMFRI has prioritized 76 finfish and shellfish species that could be targeted for future expansion of mariculture production in the country (Ranjan et al., 2017). Most of these technologies have either been transferred or are at various stages of farm-level demonstrations. The major candidate species used in coastal water cage farming include Asian sea bass, Silver pompano, Indian pompano, mullets (*Mugil cephalus*), milkfish (*C. chanos*), pearl spot (*Etroplus suratensis*), and Genetically Improved Farmed Tilapia (GIFT) (*Oreochromis niloticus*). Currently, cage farming has been reported to be economically viable. It is spreading rapidly along both coasts of the country, aided by the adoption of the technology by small-scale farmer entrepreneurs, self-help groups, and fisher societies (Gopalakrishnan et al., 2019; Aswathy et al., 2020; Jena et al., 2022).

Seaweed farming has been identified as one of the diversified-livelihood options for coastal fishers in India. However, enabling factors for significant commercial expansion and holistic development of allied industries are yet to take shape in the country (Johnson et al., 2017, 2020). Past studies (Kaladharan et al., 1996; Kaliaperumal and Kalimuthu, 1997; Rao and Mantri, 2006) have identified several commercially important seaweed species, which include red algae species such as *Gracilaria edulis, Gelidiella acerosa, and Kappaphycus alvarezii* and brown algae species such as *Sargassum wightii, Turbinaria conoides,* and *Cystoseira* spp. A number of farming techniques using floating rafts, net-tubes, long-lines, and fin fish-stocked cage-based IMTA systems have been standardized for seaweed culture. Recent literature indicated that farming of seaweed species including *K. alvarezii* and *G. acerosa*, and *Gracilaria* spp. is economically profitable as well as livelihood enhancing, thereby suitable for commercial scale-up (Mantri et al., 2022a,b). Moreover, the demand for seaweeds has been on the rise due to recent innovations involving their use in the production of secondary bioactive metabolite-based nutraceuticals, plant growth promoters, and fertilizers, besides their traditional industrial applications (Chakraborty et al., 2018; Cotas et al., 2020; Gopalakrishnan et al., 2020). A recent study by Johnson et al. (2020) identified a potential area of 23,970 ha suitable for seaweed cultivation along India's shallow coastal waters using a combination of a primary survey approach as well as a GIS-based site suitability model (Divu et al., 2020). The study took into account significant variations in geomorphology and demography, as well as a broad array of desirable biological and environmental parameters along the coastline. Presently, seaweed farming is practiced on a limited scale by several hundreds of farmers' groups along the Palk bay areas of Tamil Nadu supported by the carrageenan, agar, and seaweed-based fertilizer industries located in neighboring areas. Earlier, the farming of *K. alvarezii* experienced a boom during 2000–2013 when the local fishers along the coasts of Tamil Nadu, Gujarat, and Odisha entered into a contractual farming arrangement with PepsiCo India Holdings Ltd. followed by Aqua Agri Processing Pvt. Ltd. for carrageenan production. However, this was short-lived due to many biophysical and economic constraints (Krishnan and Narayanakumar, 2013; Johnson and Ignatius, 2020). Nevertheless, the sector is re-entering into a phase of renewed development owing to considerable policy thrust and technological and logistical advancements in recent times.

Integrated Multi-trophic Aquaculture (IMTA) is another novel mariculture practice that has been gaining momentum in recent years with its bio-mitigation potential, complementarity functions in the ecosystem, besides economic potential (Chopin et al., 2008; Barrington et al., 2009). In India, recent integrated trials carried out by ICAR-CMFRI in the Palk Bay area of Tamil Nadu involving cobia in marine cages with *K. alvarezii* in floating rafts set around the cage have shown encouraging results (Johnson et al., 2021). Similar trials involving different combinations of mullets (*M. cephalus and Liza parsia*), milkfish (*Chanos chanos*), pearl spot (*E. suratensis*), and shrimp (*Penaeus monodon, P. indicus*) as fed species, together with oyster (*Crassostrea cuttackensis, C. madrasensis*) and seaweed (*Enteromorpha* spp.) as extractive species were evaluated as viable aquaculture options in brackishwater ecosystems of the Indian Sundarban areas of West Bengal and Sindhudurg district of Maharashtra (Balasubramanian et al., 2018; Biswas et al., 2019). Recognizing the potential, fishers from Palk Bay and other parts of the southwest coast of India have started practicing IMTA-based farming operations in recent times (Johnson et al., 2021).

## 2.2. Institutions and policies

The research and development activities of mariculture in India are spearheaded mainly through public institutions and agencies functioning under the State and Union governments of India. Research on the development of culture technologies and allied areas are being led by institutions such as ICAR-CMFRI, Kochi; ICAR-CIBA, Chennai; Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI), Bhavnagar; National Centre for Sustainable Coastal Management (NCSCM), and National Institute of Ocean Technology (NIOT), Chennai. The initial stages of research were guided by isolated attempts on project mode limited to individual research institutes and Universities. Recently, coordinated research focus was brought about through network projects such as the "All India Network Project on Mariculture" of the Indian Council of Agricultural Research (ICAR) and other inter-institutional collaborative research efforts involving NCSCM, CSIR-CSMCRI, and State Universities. Additionally, development efforts in the form of training, funding as well as logistical support by Government organizations such as the National Fisheries Development Board (NFDB), Hyderabad, and the Marine Products Export Development Authority (MPEDA), Kochi have also contributed significantly to popularizing mariculture among the fisher folk and fish farmers. Most of the developmental programs are presently being supported by budgetary allocations under the *Pradhan Mantri Matsya Sampada Yojana* (PMMSY), a flagship scheme of the Union Government for fisheries development. A *draft National Mariculture Policy* was prepared in 2019 consequent to the constitution of an expert committee by the NFDB. The draft policy, which identified thrust areas for development and underlying policy imperatives, was subsequently incorporated as a part of the "*National Fisheries Policy 2020*," which is due to be notified by the Government of India and will eventually supersede all other existing policy documents in fisheries and allied sectors. Apart from this, various maritime state governments are in the process of firming-up separate state-level policies to expedite mariculture development at the grassroots level. The Government of Goa notified "*Goa State Mariculture Policy 2020*" in June 2022, which is the first of its kind in the country.

# 3. Materials and methods

## 3.1. Conceptual framework

The concept of sustainable intensification (SI) in aquaculture production systems aims to attain at least one of the following objectives, viz., (1) improved production and resource use efficiency, w.r.t. land, water, feed, and energy; (2) enhanced environmental benefits; (3) strengthened economic viability and farmers' resilience; and (4) improved social acceptance and equality and, to not compromise on the rest (FAO, 2016). The concept has its roots in African small-holder agriculture (Pretty, 1997) and summarily deals with producing more for less while minimizing negative environmental impacts and optimizing societal benefits (Little et al., 2018). Most of the literature on SI in aquaculture is empirical, wherein improvements in resource use efficiency and the contribution of specific technologies toward SI are measured using a set of objectively measurable indicators. These generally cut across various domains such as productivity, nutrition, economic viability/feasibility, human and animal wellbeing, environmental sustainability, biodiversity conservation, and social acceptability (Garnett et al., 2013; Smith et al., 2017) (Figure 1). On the other hand, a few recent studies have adopted life cycle assessment (LCA) as a framework for evaluating SI by covering the multiple impact pathways along the entire production chains (Cao et al., 2011; Henriksson et al., 2018).

This paper follows the basic premises and principles related to the concept of SI to assess the level of readiness of

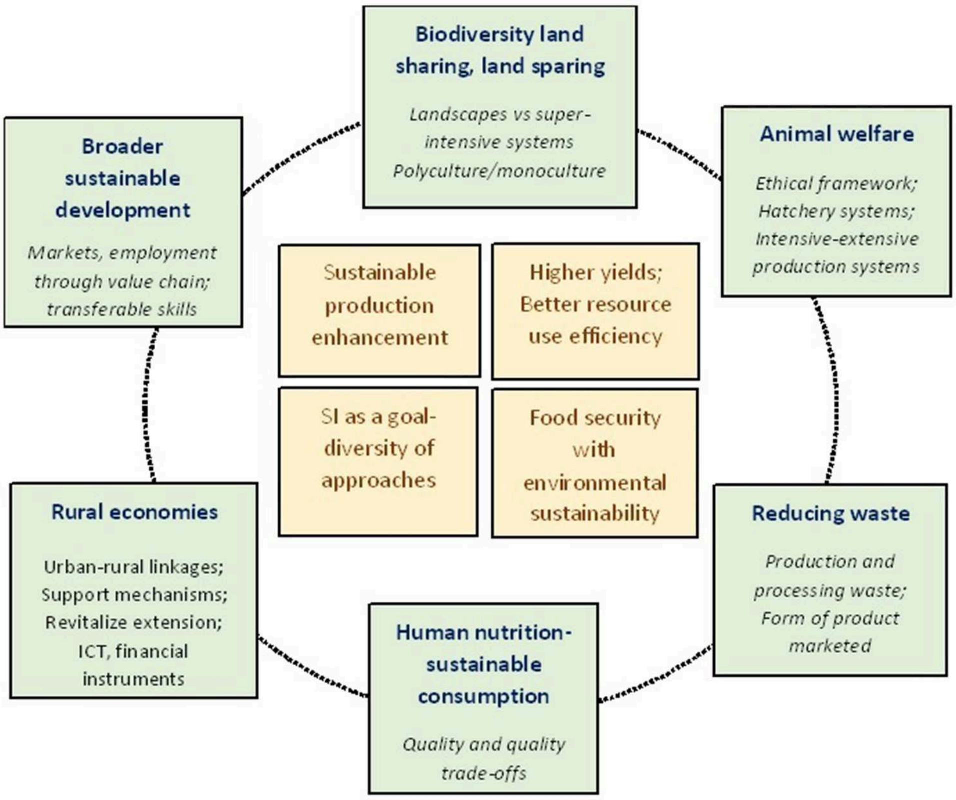


FIGURE 1
Main pillars of sustainable intensification (adapted from Garnett et al., 2013; Little et al., 2018).

the mariculture production system in India to embark on an intensification pathway that is consistent with economic, environmental/ecological, and social dimensions of sustainability and is tuned to the country's larger commitments to ensure "sustainable blue growth." The study is novel in proposing a suitable conceptual and methodological framework for SI assessment of small-holder mariculture enterprises and one of such early attempts in the country.

## 3.2. Study area

The study mainly encompasses the emerging mariculture hotspots in the country and covers five out of ten maritime states, namely, Tamil Nadu and Andhra Pradesh along the east coast; Kerala, Karnataka, and Gujarat, on the west coast of India. Apart from these, data were also collected from Diu, a Union Territory (UT) enveloped by the state of Gujarat. The specific locations are depicted in Figure 2, and their coverage in the primary surveys pertaining to various mariculture enterprises is presented in Table A1. The selection of locations for the survey was driven by predetermined criteria that include: (i) a reasonably high presence of operating mariculture units, practicing any one, or more, of the selected enterprises covered in the study, (ii) the presence of auxiliary enterprises such as seed production centers/hatcheries, fish markets, processing units, etc. in nearby locations, and (iii) known linkages of the entrepreneurs with research and development institutions and agencies dealing with marine/coastal aquaculture. Such criteria were imposed to ensure that the multiple dimensions associated with viable and sustainable mariculture, including social and institutional pre-conditions and forward and backward integration vis-a-vis fish input and product value chain nodes, can be adequately understood.

## 3.3. Data and analytical approach

As noted above, the study was primarily inspired by the necessity to document and describe the techno-economic, techno-environmental and social dimensions associated with the proposed "blue economy" targets set by the Government of India, which envisages SI of mariculture in the near future [(Government of India (GoI), 2019)]. In this context, the "techno-economic" dimension signifies an integrated assessment of the technological performance and economic feasibility of a production system, process, or value chain to identify the underlying parameters for investment and resource allocation decisions (Kobos et al., 2020). On the other hand, the "techno-environmental" dimension relates to the trade-offs between technological interventions and associated environmental/ecological parameters for viable and sustainable management of a production system (Wan and Liu, 2010; Cossutta et al., 2022). Toward this objective, the data

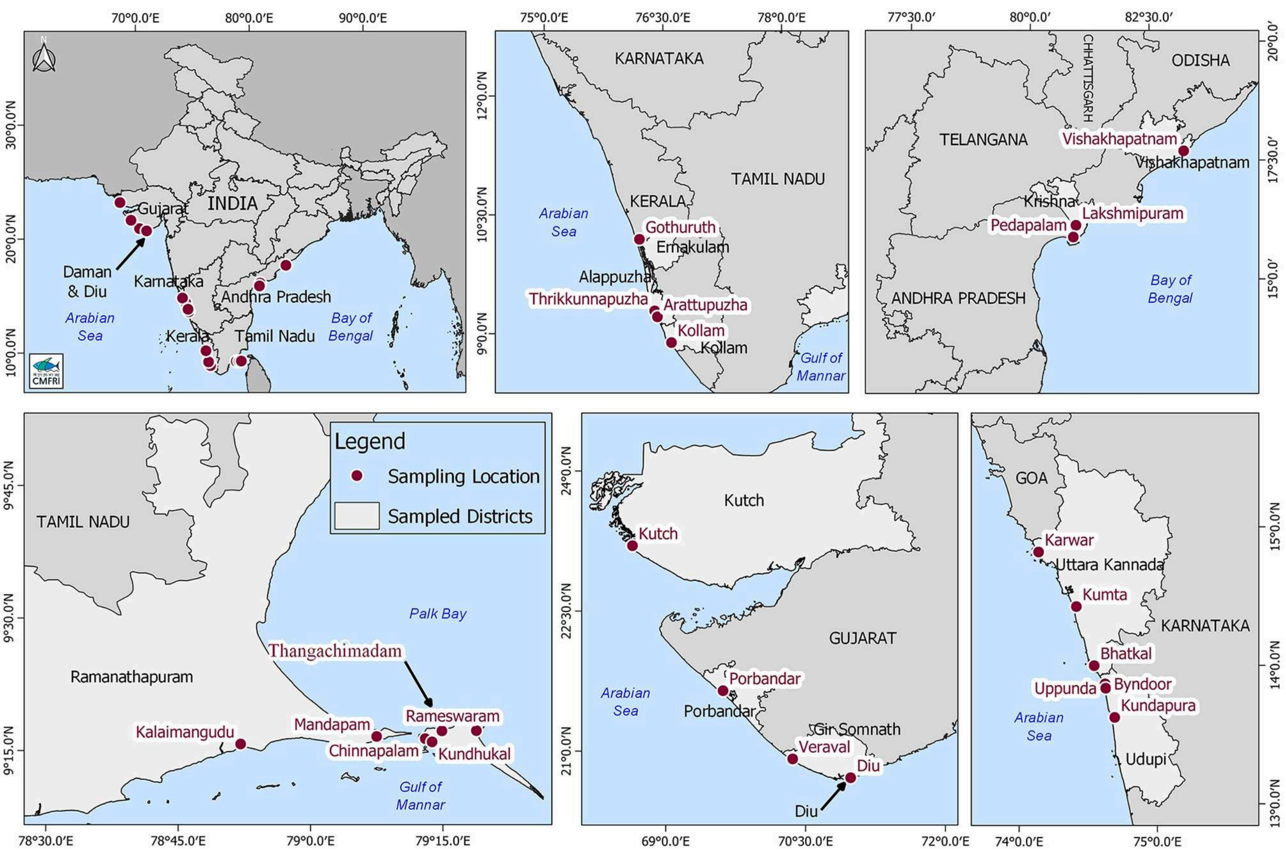


FIGURE 2
Map depicting the sampling locations of the study.

collection using primary sample surveys was closely guided by the SI framework and based on the detailed mapping of various mariculture facilities and associated stakeholders along the east and west coasts. The first phase of this process mainly involved in-depth discussions with scientists and practitioners related to mariculture research and development activities in each identified location. Subsequently, a set of semi-structured questionnaires were developed, specific to each identified enterprise, which was subsequently pretested and fine-tuned to suit location-specific and contextual variables. As the study covered a wide range of topics, languages, and diverse societal conventions, the data collection was facilitated by identifying enumerators from respective study locations. This process was relatively easier for the present study, as the author-investigators are attached to various research stations/centers of ICAR-CMFRI/ICAR-CIBA located on either coast and were in constant contact with the key informants in respective locations as part of their routine research activities. As such, no focus group discussions (FDGs) were carried out; nevertheless, the findings obtained from the questionnaire-based field data were later triangulated with key informants and experts (scientific and technical staff working in the study locations, State Department officials, etc.) for validation. The questionnaires used for the primary survey are annexed as Supplementary material. The selected mariculture enterprises include (i) open sea cage farming, (ii) coastal water cage farming, (iii) IMTA, and (iv) seaweed farming. Even though farming of bivalves, mainly green mussel, is another enterprise with immense potential for sustainable intensification in India (Mohamed et al., 2016), this study did not consider including it. Such a choice was primarily driven by the fact that the hotspots of green mussel farming in the northern region of Kerala are presently experiencing a phase of decline due to several biotic and abiotic factors (Parappurathu et al., 2021) and hence an SI assessment involving it could yield potentially biased results. The surveys were administered by randomly selecting farm units in purposively selected coastal regions where mariculture has been established as an alternative livelihood option in the recent past. The sample units were randomized by obtaining a list of farm units operating in each location and randomly assigning them for the surveys. However, in areas where the investigators had relatively less prior access, the enumerators were entrusted to bring about randomization to the best of their judgment. Further, care was taken to capture the diversity in farmed species and culture practices across the sample farms in a given location by following the broad principles of stratification (though no formal stratified sampling methods were adopted). The respondents were either the owner-farmer or the farm manager responsible for the day-to-day activities of the farm units. Many of the units covered in the sample, especially those from Tamil Nadu and Andhra Pradesh were operating either with the financial support of the respective State Fisheries Departments or funded by central agencies such as NFDB. In certain farms, the capital expenditure for the fabrication of the cages was met by ICAR-CMFRI as part of its extended research trials. The specific details of the sample units covered in each identified location are presented in Table A1. Apart from the above, secondary data were gathered from various sources, including published literature, online sources, and other databases, to facilitate an objective assessment of the present status of mariculture and potential future scenarios.

The data collected at the farm level include both qualitative and quantitative variables. To establish a linkage between various dimensions of sustainability with the above variables, different sets of farm-level indicators were constructed by broadly following the Principles-Criteria-Indicators (PCI) framework as proposed by Rey-Valette et al. (2008, 2010). The PCI approach establishes a cascading relationship between principles (which express the values and issues of sustainability), criteria (variables that are most appropriate to express these principles), and indicators (variables to be measured). This approach was followed by past studies such as FAO (2011), Fezzardi et al. (2013), and Valenti et al. (2018) under varying contexts. The above framework summarily draws from various national and international standards, reference materials, and recommendations for realizing SI of aquaculture (Pretty, 1997; European Commission, 2001; Parris and Kates, 2003; Liu and Ou, 2007). However, to use in this study, context-specific deviations were made to suit location-/enterprise-specific realities without compromising on the core ideas of the approach. Table 1 presents the key dimensions, criteria, and indicators used to assess the present level of economic viability, environmental sustainability, and social acceptability of the mariculture enterprises besides their future orientation for SI. Further, the extent to which the sample respondents are willing to adopt standard sustainable farming practices as well as risk-proofing mechanisms on-farm (Rey-Valette et al., 2008, 2010; Valenti et al., 2018; Carballeira Braña et al., 2021), over and above the existing level is assessed using their responses to a set of selected questions on a five-point Likert scale (Table 2). Most of the estimations pertaining to the techno-economic, techno-environmental, and social indicators of sustainability were performed using Microsoft Excel. However, statistical tests to assess the level of internal consistency (Cronbach's alpha) and the level of significance across parameters relating to willingness for sustainable farming and risk proofing (Kruskal-Wallis test), were carried out using STATA software, version 14.

# 4. Results

## 4.1. General features of sample farms

The sample farms belonging to each of the selected enterprises from respective locations were assessed and characterized based on a set of identified features and farming practices followed. These include the type, make, and size of the culture units, the average number of units per farm, the location of the farm in terms of depth of water and distance from the shore, major species farmed, average stocking density, type of the seeds, crop duration, feed type, feeding rate and Feed Conversion Ratio (FCR), measures in place for aeration management, antifouling, and disease management, as well harvest and yield particulars for the sample time frame. Such general features of farming, along with some specific details w.r.t. two major species cultured by the sample farms are presented in Table 3.

Most of the open sea cage farms were operated by small-scale fishers, consisting of 1–2 units by taking one crop per year. As an exception, a few farmers in Gujarat, Kerala, and Andhra Pradesh owned and operated a battery of 4–10 cages. The farm units were located in groups in suitable areas with low tidal activity, mostly within a distance of 1 kilometer from the shore where the depth was 10–15 m. Sea cage farming in the sample locations in the states of Tamil Nadu, Andhra Pradesh, and Gujarat was mainly carried out in circular marine cages made of high-density polyethylene (HDPE) or galvanized iron (GI) of 6-m diameter and 4-m depth (113 $m^3$). These are cages originally designed and popularized by ICAR-CMFRI in the late 2000s and improved upon subsequently. All the sample farms in Tamil Nadu cultured Asian Sea bass sourced from the wild for 7–8 months, whereas those in Visakhapatnam of Andhra Pradesh state grew Indian pompano and Orange-spotted grouper sourced from hatcheries for an 11-month culture duration. The spiny lobster (*Panulirus homarus*) was grown for a relatively shorter duration of 4–6 months along the coasts of Gujarat and Diu. The stocking density adopted by farms varied from 9 to 10 fish seeds/$m^3$ for Asian Sea bass; 20 to 25 seeds/ $m^3$ for Indian Pompano and Orange-spotted grouper; 12 to 15 seeds/ $m^3$ for Cobia and 20 to 30 seeds/ $m^2$ for lobster (the observed average stocking density values are presented in Table 3). The seeds required for cage culture are either collected from the wild or sourced directly from private and public hatcheries. Public hatcheries are mainly operated by research institutions such as ICAR-CMFRI, ICAR-CIBA, Rajiv Gandhi Centre for Aquaculture (RGCA), and other state-funded agencies. Certain government agencies such as NFDB through their network of Aqua One Centres and State-level aquaculture development agencies also provide subsidized seeds sourced from certified hatcheries. Variations in feeding practices across farms were noted, including both raw fish and artificial pellet feeds with varying FCRs, depending on the farmed species. The raw fish fed were mostly low-value trash fish which are less preferred for human consumption and obtained either through fishing trips as by-catch or sourced from the local market at cheap prices. Some farmers also reported having cultured mono-sex tilapia and other similar fast-proliferating species for feed purposes. Most farmers followed a mixed feeding regime, i.e., formulated pellet feed in the initial phases of the crop, which raw fish gradually substitute in advanced growth stages. The feeding rate varied depending on the feed type and the phase of the crop. Crop management in terms of aeration, anti-fouling treatments, and disease mitigation was rather weak in most of the sampled locations. Manual cleaning of nets was carried out at regular intervals by a select few farmers in Andhra Pradesh to control fouling. Similarly, as a disease management measure, only a few farmers from Andhra Pradesh have reported using probiotic bacterial consortia as a prophylactic measure to check disease incidence. Staggered harvesting of the mature crop was not common, and most farms carried out harvesting at a single stretch. Yields varied widely depending on the location and the species

TABLE 1 Summary of key dimensions, criteria, and indicators as per PCI approach to assess the level of sustainability associated with selected mariculture enterprises in sample locations in India, 2022.

| Dimension (principle) | Broad criteria | Key indicators/metrics |
|---|---|---|
| A. Techno-economic dimensions | | |
| I. Entrepreneurial readiness of farmers/entrepreneurs | Farming experience; Access to capital; General education/Technical skills; Access to technology and outside technical expertise; Availability of family/hired labor; Owned land/leased land/water body; Technical training | Permanence in activity (PA) = Average farming experience of the farmer in years |
| | | Capital self-sufficiency (CS) = Percent of farm operators in the sample having met more than half of capital expenditure from own funds |
| | | Family labor share (FL) = Average share of family labor in total labor across sample farms |
| | | The legitimacy of access (LA) = Percent of the sample farm units that reported ownership rights or existence of legal contract over the water body used for culture |
| | | Formal training (FT) = Percent of sample farms that reported having acquired formal training by the proprietor in mariculture |
| | | Access to technology and institutions (AT) = Percent of sample farms reported accessing technological support from a formally recognized source (Research institute/KVK, etc.) |
| II. Backward linkages with input markets and support services | Level of access to quality fish seeds/fingerlings, quality feeds, and other inputs; Access to institutional credit | Quality seed use (QS) = Percent of sample farms that reported sourcing quality seeds from credible sources (%) |
| | | Formulated feed use (FF) = Percent of sample farms that reported using formulated feeds |
| | | Institutional credit access (IC) = Percent of sample farms that have reported an outstanding credit from institutional sources |
| | | Institutional credit availed (ICA) = Average value (Indian Rupees, INR) of the institutional loan across sample farms |
| III. Market access and value chain integration | Access to markets for the sale of fish harvested; Fair choice of markets (diversity of markets) to sell harvested fish; Assured price at farm gate; Absence of unfair trade practices; Linkage with value addition/processing facilities | Diversity of markets (DIV) = Number of marketing options (first sale) exercised by sample units |
| | | Marketing agreement (MA) = Percent of sample farms that reported entering into a prior formal contract for marketing their produce |
| | | Unfair market practices (UMP) = Percent of sample farms that reported one or more unfair market practices encountered while selling their produce |
| | | Market commission rate (CR) = Prevailing commission rate (%) at the point of the first sale |
| | | Value addition orientation (VAO) = Percent of sample farms having direct linkages with value addition centers |
| IV. Profitability and viability of the enterprise | Level of existing production and yield; Economic returns over the cost incurred; scope for scale-up | Net operating Income (NOI) = (Gross returns) – (Operating costs) (INR) |
| | | Net profit (NP) = (Gross returns) – (Total cost) (INR) |
| | | Returns on Investment (ROI) = (Net profit) /(Initial investment costs) |
| | | Benefit-Cost Ratio (BCR) = Present value of benefits/Present value of costs |
| | | Operating Ratio (OR) = Operating cost/Gross revenue |

*(Continued)*

TABLE 1 (Continued)

| Dimension (principle) | Broad criteria | Key indicators/metrics |
|---|---|---|
| **B. Techno-environmental dimensions** | | |
| I. Technical measures for crop sustenance | Adoption of recommended stocking density; Diversity of products; degree of mechanization; Use of renewable sources of energy; Measures adopted for disease control; Standard management practices for hygiene and healthy fish stock; farm surveillance mechanisms | Stocking density deviation (SDD) = Percent deviation w.r.t recommended stocking density* for each species cultured |
| | | Species diversity (SD) = Number of all farmed species (fish/shellfish/seaweed) across sample farms over the last three crop seasons |
| | | Mechanization (MCH) = Percent of sample farms having reported using any major means of farm mechanization (automation of farm operations/climate control, etc.) |
| | | Renewable energy access (RE) = Percent of sample farms that depend mainly on renewable sources (solar, wind, etc.) for energy |
| | | Management adequacy (MA) = Percent of sample farms with at least one scientific measure adopted for disease control, hygiene management, and maintenance of healthy fish stock |
| | | Farm surveillance (FS) = Percent of sample farms with measures in place for surveillance of the farm against poaching risk |
| II. Measures in place to ensure environmental sustainability | Measures for antifouling; Measures to check water body pollution (eutrophication, organic pollution, chemicals, heavy metals, antibiotics, siltation, etc.); Crop calendar and crop holidays practiced | Antifouling management (AFM) = Percent of sample farms with at least one measure in place for antifouling management |
| | | Water quality monitoring (WQM) = Percent of sample farms with at least one measure in place for water quality monitoring |
| | | Crop holiday management (CHM) = Percent of sample farms observing crop holidays for at least 3 months in a year |
| **B. Social dimensions** | | |
| I. Social capital/community capital for sustainable intensification | Access to scientific/technical institutions for technical/extension support; Co-operatives/FPOs/NGOs; Government policies/legislations | Institutional linkage (IL) = Percent of sample farms having reported working linkage with scientific and technical institutions for technical and extension support |
| | | Social engagement (SE) = Percent of the sample respondents having reported membership in Co-operatives/FPOs/other similar organizations |
| II. Potential for enhancing social welfare | Measures in place for crew safety; Potential for employment generation; Potential for gender inclusivity and women empowerment; Measures adopted for social protection | Employment generation (EG) = Average employment generated per crop (man-days) |
| | | Gender inclusion (GI) = Average women-labor days generated as a share of the total labor generated per crop |
| | | Crew insurance (CI) = Percent of sample farms reported having farm crew insurance |
| | | Crew safety (CS) = Percent of sample farms reported having safety gears for the farm crew |
| | | Social protection (SP) = Percent of sample farms reported having enrolled in government social protection programs |

*The recommended stocking density estimates were mainly obtained from National Fisheries Development Board (NFDB) (2018). Standard stocking density recommendation from ICAR-CMFRI was used for species that are not included in National Fisheries Development Board (NFDB) (2018). Mid-point is taken in cases where recommended stocking density is expressed as a range.

TABLE 2 Summary of key dimensions, criteria, and indicators as per PCI approach followed to assess future readiness of sample respondents for sustainable intensification of mariculture.

| Dimension | Indicators of sustainable practices | Metric used |
|---|---|---|
| Willingness to embrace standard sustainable practices (over and above existing level) | **Willingness to:** adopt and invest in new technology; follow scientific farming practices through regular follow-up; attend technical training; pay for certified farm inputs; farm genetically improved species from recognized sources; perform water quality tests before each crop; switch to green energy; extend crop holidays; adoption of Good Management Practices (GMPs); adopt farm hygiene /product safety measures; enhance linkages with farmer societies/SHGs/FPOs/Government bodies/community organizations/other; act as a master trainer to promote successful technologies; conduct periodic farm auditing by the third-party agency; diversify and scale-up farm activities; increase the scale of farm production in near future; vertical integration including marketing/processing/other business ventures | Relative Importance Index for Willingness to Sustainable Farming $(\mathrm{RII_{sf}}) = \sum_{r=1}^{5} \frac{w.r}{A.N}$<br>$w =$ *frequency of responses for rank "r" on a scale* 1 *to* 5 *for* $i^{th}$ *sustainability criterion* (*given in column* 2)<br>$r =$ *Respective ranks*<br>$A =$ *Highest rank in the scale* (5)<br>$N =$ *Total number of respondents in the sample* |
| Readiness to adopt standard risk proofing mechanisms (over and above existing level) | **Readiness to**: adopt labor safety measures on farm; use security/surveillance tools; to pay for aquaculture insurance/farm crew insurance; enroll in social security/welfare registration for farm crew; notify/register employment of migrant laborers; access weather alert platforms; monitor incidence of harmful algal blooms (HAB); join disease surveillance platforms; check/monitor invasive bio-foulers in farms | Relative Importance Index for Readiness for Risk Proofing $\left(\mathrm{RII_{rp}}\right) = \sum_{r=1}^{5} \frac{w.r}{A.N}$<br>$w =$ *frequency of responses for rank "r" on a scale* 1 *to* 5 *for* $i^{th}$ *risk proofing mechanism* (*given in column* 2)<br>$r =$ *Respective ranks*<br>$A =$ *Highest rank in the scale* (5)<br>$N =$ *Total number of respondents in the sample* |

cultured, with the highest being 16 kg/m$^3$, reported by the sample farmers culturing Indian Pompano in Vishakhapatnam (Table 3).

Compared to open sea cages, coastal water cages were smaller in size and rectangular in shape, generally made of galvanized iron (GI). However, isolated cages made of bamboo wood were also observed in certain regions. Their dimensions varied from case to case, but were generally within 75 m$^3$ in volume. As in the case of sea cage farmers, coastal water cage farmers were also smallholders, each operating 1–2 units, taking one crop of 6–12 months. The farms were mostly located in internal backwater areas or estuaries, very close to the shore (15–200 m), where the water depth ranged from 2 to 10 m. These farms are generally owned and managed by small families mainly using domestic labor. The Asian sea bass was the most preferred species across all sample locations, but other amenable species such as red snapper, silver pompano, and Indian pompano are also being cultured. In certain locations, brackishwater species such as pearl spot and mullets were also cultured along with the above species. However, the sample farms did not report any of them as major farmed species, except in Ernakulam and Alappuzha districts of Kerala, where farmers grew pearl spot either as the main crop or in the outer nets of the cages (100–200 seeds/cage) to minimize biofouling. Greater variations in stocking density were observed across sample locations, which ranged from 7 to 40 seeds/m$^3$ for Asian Sea bass; 10 to 40 seeds/m$^3$ for red snapper; 30 to 80 seeds/m$^3$ for silver pompano and 8 to 10 seeds/m$^3$ for Indian pompano. In Karnataka, where polyculture using Asian sea bass and red snapper are practiced, bigger seeds (of about 200 g) were stocked to address the problem of cannibalism. Variations in feeding practices across farms were also noted, with most of them using raw fish 1–2 times a day with FCR ranging from 6:1 to 7:1 depending on the farmed species and the type of raw fish used. Formulated pellet feed was used for feeding hatchery-based Asian sea bass grown in the sample farms of Karnataka and Kerala and Indian pompano and silver pompano, respectively in Kerala and Andhra Pradesh. In many cases, a combination of raw fish and pellet feeds was used depending on the growth phase of the crop at varying feeding rates. Owing to the proximity of the cages from the shore, the coastal water cage farmers were seen to follow better crop management practices than the sea cage farmers. Manual cleaning and regular changing of nets were common practices to minimize fouling of the cages. Most farmers in Kerala and Andhra Pradesh applied chemicals such as potassium permanganate, methylene blue, vitamin C, etc. to reduce the incidence of diseases. A limited number of farmers in Karnataka and Andhra Pradesh (two each) reported using probiotic bacterial consortia as a prophylactic measure to minimize disease incidence in their cages. The usage of antibiotics was not reported in any of the farms, except for random instances of applying them by a couple of backwater cage farmers. The sample farmers generally harvested grown fish 1–2 times per crop. However, a few reported having practiced staggered farming (3–5 times) extended over a period, either as a measure to capitalize on price variations or as a distress measure to meet operating costs. As in the case of marine cage farms, crop yields varied widely, and ranged from 8 to 16 kg/m$^3$ on average across sample locations and farmed fish species. The highest yield (18.3 kg/m$^3$ on average) was reported by farmers practicing polyculture of Asian sea bass and red snapper for an extended crop duration ranging from 8 to 18 months in the Karnataka state (Table 3).

The IMTA farms covered in the study were of two types: (i) open sea cage farming of cobia integrated with red seaweed (*K. alvarezii*) in the Mandapam region of Tamil Nadu state and (ii) coastal water cage farming of Asian sea bass and red snapper integrated with green mussel in the Byndoor region of Karnataka state. In the former case, each unit consisted of one HDPE circular cage, encircled by about 16 seaweed rafts nearby. The units were located about 1 km from the shore at a water depth of 5–6 m. The

TABLE 3 General features of sample farms practicing mariculture in the selected coastal regions of India.

| Feature | | Sample locations | | |
|---|---|---|---|---|
| I. Open sea cage farming | | | | |
| | | Tamil Nadu | Andhra Pradesh | Gujarat |
| Type of the cage | | Circular HDPE cage ($n = 20$) | Circular HDPE cages ($n = 7$) | Circular GI and HDPE cages ($n = 14$) |
| Average number of units/farm (owned by a person/group) | | 1.3 | $10^{\#}$ | 2.7 |
| Size of the unit (Dia × D) in m | | 6 × 4 | 6 × 4 | 6 × 6 (HDPE); 5 × 4.5 (GI) |
| Distance from the shore (m) | | 1,000 | 500–750 | 500–800 |
| Depth of water (m) | | 5–6 | 10 | 8–15 |
| Major species farmed | | Asian sea bass (ASB) | Indian pompano (IP), Orange spotted grouper (OSG) | Lobster |
| Average stocking density (Number/m$^3$) | Species 1 | 12.20 (SD = 4.4, $n = 20$) | IP: 21.8 (SD = 4.1, $n = 4$) | 28.2 (Number/m$^2$) (SD = 5.0, $n = 14$) |
| | Species 2 | – | OSG: 25.0 (SD = 4.2, $n = 3$) | |
| Type of seed (Wild/SPF/other) | Species 1 | Wild | IP: Hatchery | Wild |
| | Species 2 | – | OSG: Hatchery | – |
| Crop duration (months) | Species 1 | 7–8 | IP: 11 | 4–6 |
| | Species 2 | – | OSG: 11 | – |
| Feed type (raw fish/locally formulated/concentrate/pellet) | Species 1 | Trash fish | IP: Trash fish, Formulated pellet feed | Trash fish |
| | Species 2 | – | OSG: Raw fish | – |
| Feeding rate (kg/day)* | Species 1 | 20–25 (1–2 times) | IP: 1–4 (pellet, 1–2 times) | Lobster: 10–12 (1–2 times) |
| | Species 2 | – | OSG: 20–25 (1–2 times) | – |
| Feed conversion ratio (FCR) | Species 1 | 6:1 (raw fish) | IP: 2:1 (pellet) | Lobster: 6:1 (raw fish) |
| | Species 2 | – | OSG: 6:1 (raw fish) | – |
| Antifouling/other treatments | | None | Manual cleaning of nets (once a month) | Manual cleaning of nets (once a month) |
| Disease management | | Fresh water treatment (nursery) | Freshwater treatment (nursery), probiotic bacteria supplement | None |
| Number of harvests/crop (Single/staggered) | Species 1 | 1 | IP: 1 | Lobster: 1 |
| | Species 2 | 1 | OSG: 1 | – |
| Average yield (kg/m$^3$/unit) | Species 1 | 10.7 (SD: 1.5, $n = 20$) | IP: 16.0 (SD: 0.4, $n = 4$) | Lobster: 3.7 (SD: 0.2, $n = 14$) |
| | Species 2 | – | OSG: 13.3 (SD: 0.2, $n = 3$) | – |

*(Continued)*

TABLE 3 (Continued)

| Feature | | Sample locations | | |
|---|---|---|---|---|
| 2. Coastal water cage farming | | | | |
| | | Karnataka | Kerala | Andhra Pradesh |
| Type of the cage | | Rectangular GI ($n = 34$) | Rectangular GI cage ($n = 30$) | Rectangular GI cage ($n = 10$) |
| Average number of units/farm (owned by a person/group) | | 1.5 | 1.1 | 1.6 |
| Size of the unit (L × B × D) in m | | 6 × 3 × 2 ($n = 21$); 4 ×4 × 3 ($n = 7$); other ($n = 6$) | 4 × 4 × 3 (27); 6 × 6 × 4 (3) | 5 × 5 × 3 |
| Distance from the shore (m) | | 10–200 | 10–100 | 15–100 |
| Depth of water (m) | | 3–6 | 2–5 | 4–10 |
| Major species farmed | | Asian sea bass (ASB); Red snapper (RS) | ASB, Pearl spot (PS) | ASB, Indian Pompano (IP) |
| Average stocking density (Number/$m^3$) | Species 1 | ASB: 21.3 (SD = 7.3, $n = 21$) | ASB: 30.5 (SD = 12, $n = 16$) | ASB: 10.0 (SD = 3.4, $n = 4$) |
| | Species 2 | RS: 32.7 (SD = 15.1, $n = 7$) | PS: 36.3 (SD = 9.2, $n = 14$) | IP: 12.3 (SD = 4.2, $n = 6$) |
| | Poly-culture | ASB+RS: 42.8 (SD = 7.7, $n = 6$) | – | – |
| Type of seed (Wild/SPF/Other) | Species 1 | ASB: Wild; Hatchery | ASB: Hatchery; SPF | ASB: Wild; Hatchery |
| | Species 2 | RS: Wild | PS: Hatchery; SPF | IP: Hatchery |
| Crop duration (months) | Species 1 | ASB: 8–12 | ASB: 8–12 | ASB: 6–7 |
| | Species 2 | RS: 8–18 | PS: 8–12 | IP: 5–7 |
| Feed type (raw fish/locally formulated/concentrate/pellet) | Species 1 | ASB: Raw fish, Formulated pellet feed | ASB: Formulated pellet feed | ASB: Trash fish |
| | Species 2 | RS: Trash fish | PS: Formulated pellet feed | IP: Formulated pellet feed |
| Feeding rate (kg/day)* | Species 1 | ASB: 3–6 (pellet, 1–2 times) | ASB: 3–4 (pellet, 2–3 times) | ASB: 20–25 (raw fish, 2 times) |
| | Species 2 | RS: 10–15 (raw fish, 1–2 times) | PS: 2–3 (pellet, 2–3 times) | IP: 2–3 (pellet, 2 times) |
| Feed conversion ratio (FCR) | Species 1 | ASB: 6:1 (raw fish) | ASB: 2:1 (pellet) | ASB: 5:1 (raw fish) |
| | Species 2 | RS: 5:1 (raw fish) | PS: 2:1 (pellet) | IP: 2:1 (pellet) |
| Antifouling/other treatments | | Manual cleaning, net change | Manual cleaning (once a month) | Manual cleaning (once in 2 months) |
| Disease management | | None followed by most units; probiotic bacteria supplement ($n = 2$) | Disinfectant treatment—Potassium permanganate ($n = 12$), Methylene blue ($n = 10$) | Application of Vitamin C ($n = 3$); Other immune-stimulants ($n = 4$) |
| Number of harvests/crop (Single/staggered) | Species 1 | ASB: 1–3 | ASB: 1–3 | ASB: 1–2 |
| | Species 2 | RS: 2–3 | PS: 2–3 | IP: 1 |
| Average yield (kg/$m^3$/unit) | Species 1 | ASB: 9.2 (SD: 4.8; $n = 21$) | ASB: 16.6 (1.6, $n = 16$) | ASB: 6.3 (SD: 3.5; $n = 4$) |
| | Species 2 | RS: 8.9 (SD: 2.6; $n = 7$) | PS: 5.9 (3.5, $n = 14$) | IP: 8.3 (SD: 3.3; $n = 6$) |
| | Poly-culture | ASB+RS: 18.3 (SD: 5.8; $n = 6$) | – | – |

TABLE 3 (Continued)

| Feature | | Sample locations | |
|---|---|---|---|
| II. Integrated multitrophic aquaculture (IMTA) | | | |
| | | Tamil Nadu | Karnataka |
| Type of the unit | Fish/shellfish cage | Circular (HDPE/GI) cages ($n = 10$) | Rectangular wooden cages ($n = 4$) |
| | Mussel/seaweed raft | Rectangular wooden rafts | Rectangular wooden rafts |
| Average number of units/farm | IMTA | 1.1 | 1.2 |
| Size of the unit (L × B × D)/(Dia × D) in m | Fish/shellfish cage | 6 × 6 | 6 × 4 × 4 (rectangular) |
| | Mussel/seaweed raft | 3.6 × 3.6 | 6 × 6 |
| Distance from the shore (m) | | 1,000 | 10–300 |
| Depth of water (m) | | 5–6 | 4–9 |
| Major species farmed | Fed species | Cobia | Asian sea bass (ASB); Red snapper (RS) |
| | Extractive species | Red seaweed (*Kappaphycus alvarezii*) (KA) | Green mussel (GM) |
| Average stocking density (Number/$m^3$) | Fed species | Cobia: 7.7 (SD = 1.8, $n = 10$) | ASB: 13.5 (SD = 2.1, $n = 2$); RS: 12 (SD = 2.8, $n = 2$) |
| | Extractive species | KA: 77.1 (kg/raft/cycle), (SD = 2.3, $n = 10$) | GM: 1–2 kg seeds/rope; 50–100 ropes/raft; 1–2 rafts/IMTA unit |
| Type of seed (Wild/SPF/Other) | Fed species | Cobia: Hatchery | ASB: Hatchery; RS: Wild |
| | Extractive species | KA: Cultured | GM: Wild |
| Crop duration (months) | Fed species | Cobia: 7–8 | ASB and RS: 8–12 |
| | Extractive species | KA: 45 (days), (4 cycles/year) | GM: 5–7 |
| Feed type (raw fish/locally formulated/concentrate/pellet) | Fed species | Cobia: Trash fish | ASB and RS: Trash fish |
| Feeding rate (kg/day) | Fed species | Cobia: 20–30 (Trash fish, 1–2 times) | ASB and RS: 10–15 (Trash fish, 2 times) |
| Feed conversion ratio (FCR) | Fed species | Cobia: 5:1 | RS: 5:1 |
| Antifouling/other treatments | | None | Manual cleaning of nets; Change of nets |
| Disease management | | None | None |
| Number of harvests /crop (Single/staggered) | Fed species | Cobia: 1 | ASB and RS: 2–4 |
| | Extractive species | KA: Once every 45 days | GM: 1 |
| Average Yield (kg/$m^3$/unit) | Fed species | Cobia: 11.4 (SD: 1.1, $n = 10$) | ASB: 4.0 (SD: 0.2, $n = 2$); RS: 6.9 (SD: 3.93, $n = 2$) |
| | Extractive species | KA: 1,254 (kg wet weight/raft for 4 cycles) (SD: 50.3, $n = 10$ units of 16 rafts each) | GM: 7.8 kg/rope (SD: 2.5, $n = 4$) |

[#] Farming is carried out by a fisheries co-operative society and cages are established in clusters, each carrying a battery of 10.

[*] Feeding rate is expressed as the average quantity fed through the crop duration; might differ across growth phases. All the estimates pertain to the most recent cycle of the crop.

cages were stocked with cobia seeds sourced mainly from hatcheries at an average density of 5–6/m$^3$ and maintained for 7–8 months by feeding raw fish (FCR: 7:1). Seaweeds were raised in rectangular rafts in four cycles of 45 days each during a cropping season. The respondent farmers practicing this system reported having realized an average yield of 11.4 kg/m$^3$ of cobia and 1,254 kg *K. alvarezii* per raft after harvest of the crop. The coastal water IMTA units were located very close to the shore and each unit, consisted of one rectangular cage surrounded by 1–2 green mussel rafts. Each raft carried 50–100 seeded ropes suspended into the water body. The crop duration ranged from 8 to 12 months for the fed species and 5–7 months for the extractive species (green mussel). The fish in the cage was fed with raw trash fish with an FCR of 5:1. At the end of the harvest season, the average fish yield realized by the sample farmers was 4.0 kg/m$^3$ in the case of Asian sea bass and 6.9 kg/m$^3$ for red snapper. The average green mussel yield recorded for the four sample units was 7.8 kg/rope with a standard deviation of 2.5. In either type of IMTA unit, the farmers did not report any notable aeration, anti-fouling, or disease management approaches being followed (Table 3).

As noted earlier, the sample seaweed farms were mainly located in adjoining areas along the Mandapam and Rameswaram coasts of Tamil Nadu. They were operated primarily by women-centric self-help groups (SHGs) or independent smallholder farm families. All farmers grew *K. alvarezii*, the red seaweed species in floating bamboo rafts of 3.6 × 3.6 dimension at a distance of 10–30 m from the shore. Each operator owned 10–20 rafts and raised 5–6 cycles of the crop for 45 days a year. About 50–60 kg of planting material from previous crops was used to stock each raft. The farmers generally did not follow any management practices to prevent fouling or disease incidence. The respondents reported that grazing seaweeds by fish and other aquatic species was a major problem. An average wet yield of 1,177 kg/raft (SD: 104, $n = 30$) was obtained per raft per year from the sample units, which translates to 14.0 tons of wet yield per farm unit per year (SD: 4,542, $n = 30$) on average.

## 4.2. Techno-economic indicators

Techno-economic viability of aquaculture units depends mainly on farm-level factors, the local economy's degree of openness, and general economic development status (Boyd et al., 2020). The estimates of techno-economic indicators in respect of the sample farms are presented in Table 4. Among all, experience in mariculture (permanence in activity, PA) was highest for cage farmers operating in the Vishakhapatnam region of Andhra Pradesh state (11.4 years on average), followed by IMTA farmers in Karnataka (8.8 years) and seaweed farmers in Tamil Nadu (7.8 years). Indicators for self-sufficiency in capital and labor, which are important determinants of economic viability in smallholder farms, showed mixed results. Legitimacy of access (LA), which indicates whether a farm possesses legal farming rights over the water body, was reported in the coastal waters of Karnataka and some parts of Kerala only. In other locations, farming was taken up without any authorization from the government agencies concerned. The majority of the respondents across states reported having acquired necessary technological inputs and formal training from recognized sources such as research institutes, *Krishi Vigyan Kendras* (KVK), or other state government agencies. Similarly, access to quality seeds was fairly good in most locations except in Gujarat and Karnataka, where <50% of farmers only received good quality seeds for culture. On the other hand, the use of formulated feeds depended upon the species cultured and the level of market access to feeds in adequate quantities. Survey data suggested that, while most of the farmers in Andhra Pradesh and Kerala and some of them (23.5%) in Karnataka fed formulated pellet feeds to standing fish stock, others relied on low-value trash fish for the purpose. Access to institutional credit to meet capital and operational expenses were reported to be a major limiting factor for mariculture farmers across the board, except for a few, in the states of Karnataka and Kerala. The harvested fish was sold mostly in local markets as indicated by the indicators, Diversity of Markets (DIV). The coastal water farmers in Karnataka reported having access to up to five domestic market formats, whereas most others depended on farm gate and wholesale only. Prior marketing contract for fish was reported only by 20 percent of the coastal water farmers in Tamil Nadu while a few respondents in Andhra Pradesh and Karnataka incurred commission charges (ranging from 3.5 to 7.0%) for the first sale of fish to the local market agents. Notably, a significant proportion of sample farmers engaged in coastal water cage farming, IMTA, and seaweed farming in Karnataka, Kerala, Andhra Pradesh, and Tamil Nadu reported having encountered various forms of unfair market practices such as under-pricing, weight manipulation, and excess market commission.

The results on financial viability and profitability of sample farms reflected through indicators such as net profit (NP), net operating income (NOI), returns on investment (ROI), benefit-cost ratio (BCR), and operating ratio (OR) are presented in Figures 3, 4. While Figure 3 indicates the absolute level of profitability adjusted for costs of the farm units, Figure 4 shows the relative viability of the units based on ratios. Among open sea cage culture units, those from Andhra Pradesh realized greater profitability than those from other locations. Similarly, coastal water cage units operating from Kerala displayed much higher profitability in relation to others, with all sample units realizing NOI greater than INR 100,000 per crop. Though marine cage farmers generally fared better in terms of absolute indicators of profitability owing to the greater size of culture units, they were trailing behind other enterprises in terms of relative profitability indicators such as ROI, BCR, and OR. While most of the units in the entire sample were observed to be profitable on all indicators, a few of them, especially those practicing open sea cage culture in Tamil Nadu, as well as coastal water cage culture and IMTA in Karnataka and Andhra Pradesh reported having incurred losses during the period under study.

## 4.3. Techno-environmental indicators

The results of techno-environmental indicators are presented in Table 4. In general, most of the sample farms were found to understock their culture units mainly because of a shortage of quality seeds and their relatively high cost. Only the lobster cage farmers in Gujarat followed greater stocking density than recommended, as they are capture-based aquaculture (CBA) units.

**TABLE 4** Estimated sustainability indicators associated with selected mariculture enterprises in sample locations in India, 2022.

| Key indicators/metrics | Open sea cage farming | | | Coastal water cage farming | | | IMTA | | Seaweed farming |
|---|---|---|---|---|---|---|---|---|---|
| | Tamil Nadu | Andhra Pradesh | Gujarat | Karnataka | Kerala | Andhra Pradesh | Tamil Nadu | Karnataka | Tamil Nadu |
| **A. Techno-economic indicators** | | | | | | | | | |
| Permanence in activity (PA) | 1.7 (0.9) | 11.4 (5.5) | 7.3 (2.5) | 4.9 (2.7) | 5.1 (3.2) | 2.8 (1.56) | 4.9 (3.0) | 8.8 (4.8) | 7.8 (3.9) |
| Capital self-sufficiency (CS) (%) | 20.0 | 28.6 | 100.0 | 29.4 | 80.0 | 10.0 | 0.0 | NA | 100 |
| Family labor share (FL) (%) | 36.6 | 0.0 | 14.4 | 84.3 | 58.8 | 81.3 | 47.8 | 87.2 | 54.5 |
| The legitimacy of access (LA) (%) | 0.0 | 0.0 | 0.0 | 100.0 | 16.7 | 0.0 | 0.0 | 100.0 | 0.0 |
| Formal training (FT) (%) | 100.0 | 85.7 | 100.0 | 79.4 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Access to technology (AT) (%) | 100.0 | 85.7 | 100.0 | 97.1 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Quality seed (QS) (%) | 100.0 | 100.0 | 25.0 | 47.1 | 100.0 | 100.0 | 100.0 | 100.0 | – |
| Formulated feed (FF) (%) | 0.0 | 100.0 | 0.0 | 23.5 | 83.3 | 70.0 | 0.0 | 0.0 | – |
| Institutional credit access (IC) (%) | 0.0 | 0.0 | 0.0 | 64.7 | 27.0 | 0.0 | 0.0 | 25.0 | 0.0 |
| Institutional credit availed (ICA) (INR) | 0.0 | 0.0 | 0.0 | NA | 1,10,570 | 0.0 | 0.0 | NA | 0.0 |
| Diversity of markets (DIV) | 1 | 1 | 3 | 4 | 3 | 1 | 2 | 5 | 1 |
| Marketing agreement (MA) (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 20.0 | 0.0 | 0.0 |
| Unfair market practices (UMP) (%) | 0.0 | 0.0 | 0.0 | 100.0 | 13.0 | 70.0 | 70.0 | 100.0 | 100.0 |
| Market commission rate (CR) (%) | Nil | 5.0 | Nil | 7.0 | Nil | 3.5 | Nil | Nil | Nil |
| Value addition orientation (VAO) (%) | 0.0 | 0.0 | 0.0 | 0.0 | 47.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Net operating Income (NOI) (INR) | Results depicted in Figure 3 below | | | | | | | | |
| Net profit (NP) (INR) | | | | | | | | | |
| Returns on Investment (ROI) | Results depicted in Figure 4 below | | | | | | | | |
| Benefit-cost ratio (BCR) | | | | | | | | | |
| Operating ratio (OR) | | | | | | | | | |
| **B. Techno-environmental indicators** | | | | | | | | | |
| Stocking density deviation (SDD) | Results depicted in Figure 5 below | | | | | | | | |
| Species diversity (SD) | 1 | 2 | 3 | 3 | 4 | 3 | 2 | 6 | 1 |
| Mechanization (MCH) (%) | 0.0 | 71.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

*(Continued)*

TABLE 4 (Continued)

| Key indicators/metrics | Open sea cage farming | | | Coastal water cage farming | | | IMTA | | Seaweed farming |
|---|---|---|---|---|---|---|---|---|---|
| | Tamil Nadu | Andhra Pradesh | Gujarat | Karnataka | Kerala | Andhra Pradesh | Tamil Nadu | Karnataka | Tamil Nadu |
| Renewable energy access (RE) (%) | 0.0 | 100.0 | 37.5 | 5.9 | 30.0 | 40.0 | 0.0 | 0.0 | 0.0 |
| Management adequacy (MA) (%) | 10.0 | 57.1 | 0.0 | 5.9 | 56.7 | 20.0 | 0.0 | 0.0 | 0.0 |
| Farm surveillance (FS) (%) | 0.0 | 85.7 | 0.0 | 100.0 | 93.3 | 90.0 | 0.0 | 0.0 | 0.0 |
| Antifouling management (AFM) (%) | 0.0 | 100.0 | 0.0 | 100.0 | 56.7 | 100.0 | 0.0 | 100.0 | 0.0 |
| Water quality monitoring (WQM) (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Crop holiday management (CHM) (%) | 100.0 | 100.0 | 100.0 | 47.1 | 63.3 | 100.0 | 100.0 | 50.0 | 100.0 |
| C. Social indicators | | | | | | | | | |
| Institutional linkage (IL) (%) | 100.0 | 85.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100 |
| Social engagement (SE) (%) | 100.0 | 71.4 | 37.5 | 85.3 | 23.0 | 50.0 | 80.0 | 100.0 | 100 |
| Employment generation (EG) (man-days/unit) | 321.4 (56.6) | 195.3 (23.8) | 175 (54.2) | 94.3 (41.9) | 145 (45.4) | 196 (70.3) | 395.7 (111.0) | 90.2 (4.2) | 98.7 (36.0) |
| Gender inclusion (GI) (%) | 33.3 | 24.8 | 8.3 | 20.6 | 13.3 | 34.5 | 51.8 | 19.6 | 57.9 |
| Crew insurance (CI) (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Crew safety (CS) (%) | 0.0 | 85.7 | 37.5 | 94.1 | 10.0 | 100.0 | 0.0 | 100.0 | 0.0 |
| Social protection (SP) (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Number of observations | 20 | 7 | 14 | 34 | 30 | 10 | 10 | 4 | 30 |

Figures in parentheses indicate estimates of standard deviation; 1 Indian Rupee (INR) = 0.012 US Dollars.

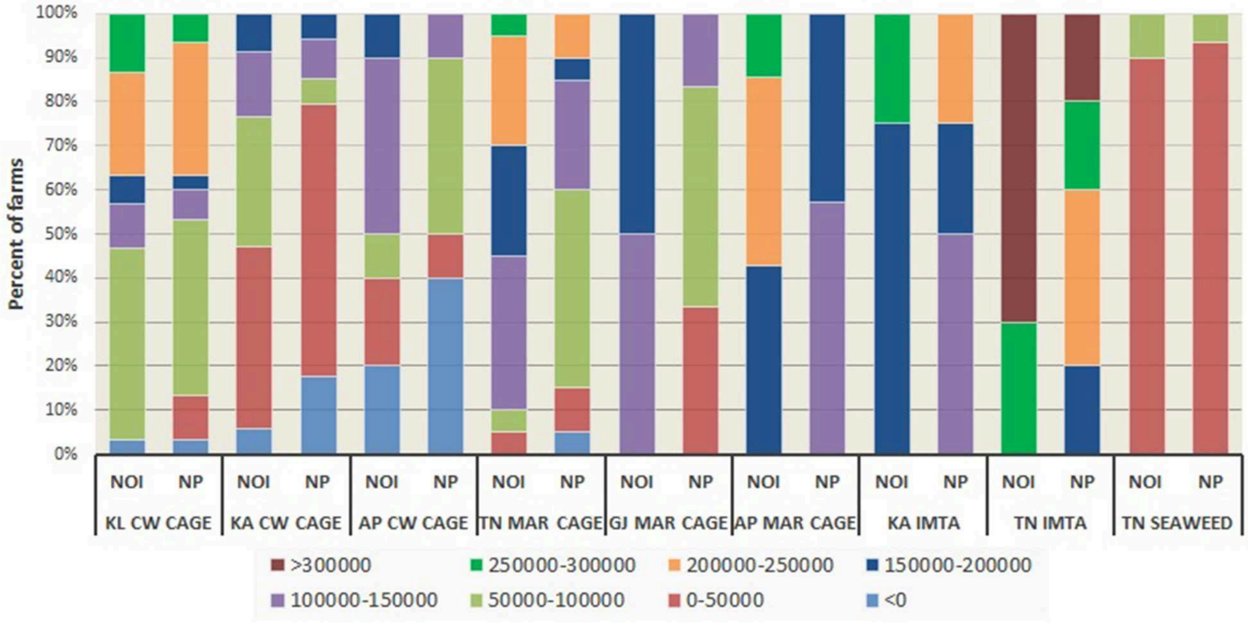


FIGURE 3
Distribution of net operating income (NIO) and net profit (NP) of sample farms. For seaweeds, income estimates are reported for a batch of 10 rafts each for the sample farmers. Profitability is expressed in Indian rupees [1 Indian Rupee (INR) = 0.012 US Dollars]. KL CW CAGE: Coastal water cage, Kerala; KA CW CAGE: Coastal water cage, Karnataka; AP CW CAGE: Coastal water cage, Andhra Pradesh; TN MAR CAGE: Marine cage, Tamil Nadu; GJ MAR CAGE: Marine cage, Gujarat; AP MAR CAGE: Marine cage, Andhra Pradesh; KA IMTA: IMTA, Karnataka; TN IMTA: IMTA, Tamil Nadu; TN SEAWEED: Seaweed, Tamil Nadu.

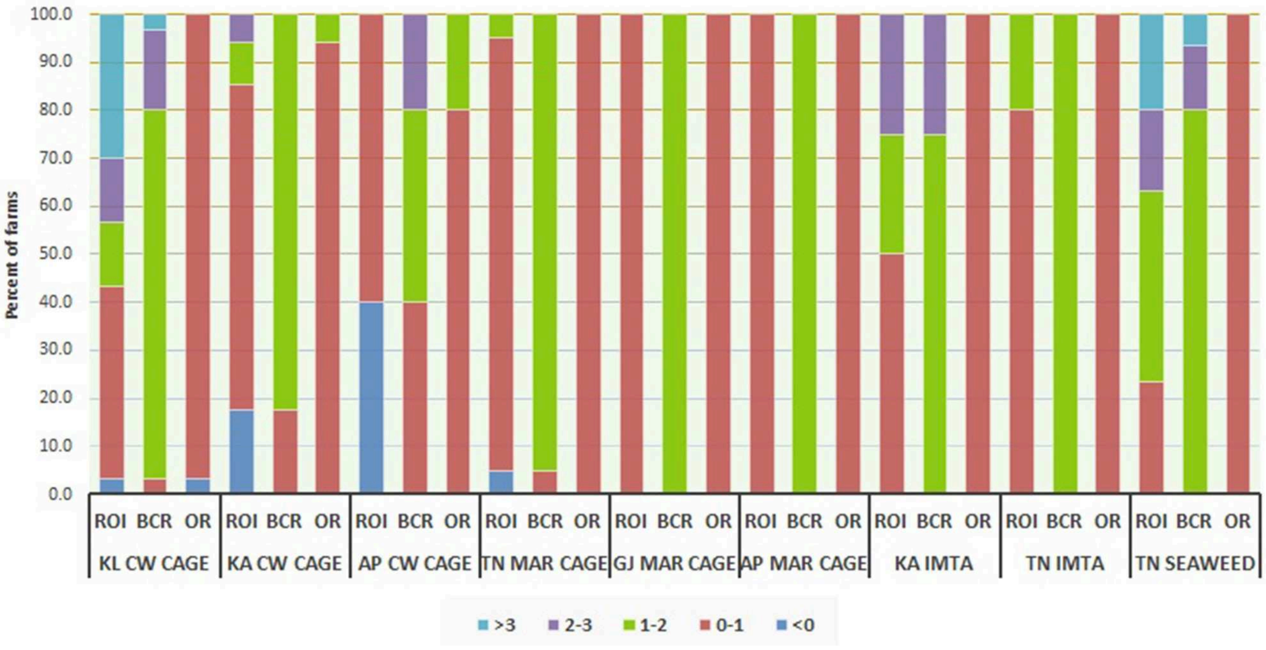


FIGURE 4
Distribution of economic viability indicators of sample farms. For seaweeds, profitability indicators are reported for a batch of 10 rafts each for the sample farmers. KL CW CAGE: Coastal water cage, Kerala; KA CW CAGE: Coastal water cage, Karnataka; AP CW CAGE: Coastal water cage, Andhra Pradesh; TN MAR CAGE: Marine cage, Tamil Nadu; GJ MAR CAGE: Marine cage, Gujarat; AP MAR CAGE: Marine cage, Andhra Pradesh; KA IMTA: IMTA, Karnataka; TN IMTA: IMTA, Tamil Nadu; TN SEAWEED: Seaweed, Tamil Nadu.

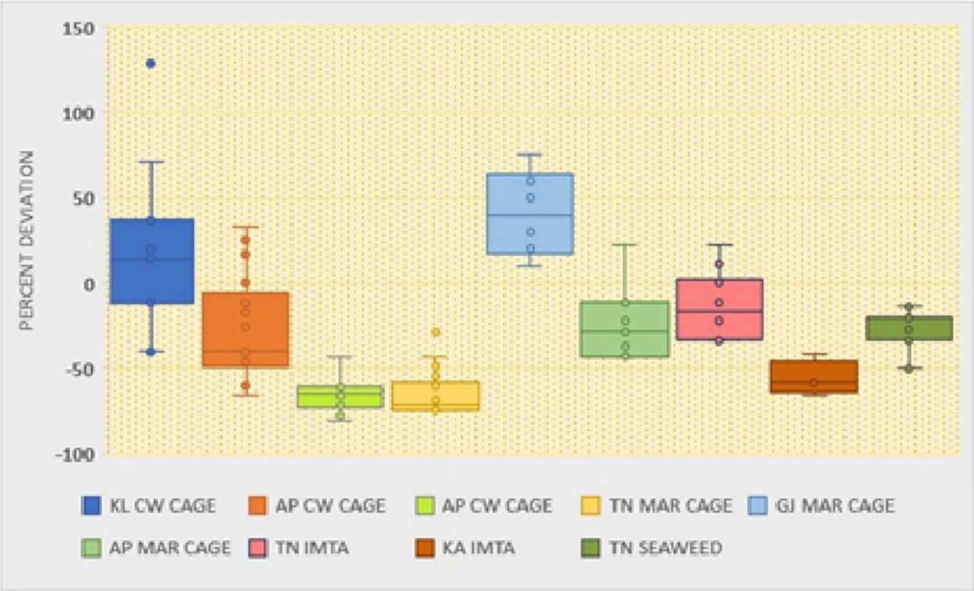


FIGURE 5
Box plot depicting percent deviation concerning recommended stocking density in sample farms, India. KL CW CAGE: Coastal water cage, Kerala; KA CW CAGE: Coastal water cage, Karnataka; AP CW CAGE: Coastal water cage, Andhra Pradesh; TN MAR CAGE: Marine cage, Tamil Nadu; GJ MAR CAGE: Marine cage, Gujarat; AP MAR CAGE: Marine cage, Andhra Pradesh; KA IMTA: IMTA, Karnataka; TN IMTA: IMTA, Tamil Nadu; TN SEAWEED: Seaweed, Tamil Nadu.

Many farmers practicing coastal water cage farming in Kerala were also reported over-stocking their cages. Species diversity (SD) that indicates the number of all farmed species in a sample location during the last three cropping seasons ranged between 1 and 6, the highest reported in IMTA farms in Karnataka (Table 4). None of the farm units, except those in Visakhapatnam (71.4%) reported any means of mechanization or automation in their farming operations. In the latter case, farmers reported attempting automated feeding in their cages on a trial basis with technical support from the Visakhapatnam Centre of ICAR-CMFRI. The use of solar energy in the farms for lighting, surveillance and, to power other minor farm operations is gradually becoming common in cage farms with varying levels of adoption across locations. Management adequacy (MA), a measure to determine the level of adoption of disease control, hygiene management, and general health management of farm stock was observed to be relatively higher among marine cages in Andhra Pradesh (57.1%) and coastal water cage farms in Kerala (81.8%). In other locations, the farmers were either non-adopters or at the initial stages of adoption. Almost all coastal water cage farms were observed to adopt farm surveillance measures like closed circuit cameras or watch and ward mechanisms, still, marine-based enterprises (except in Vishakhapatnam), were low on this aspect. The low incidence of poaching in the open sea has been cited as a reason.

The estimates of environmental sustainability indicators such as aeration management (AM) and water quality monitoring (WQM) were nil in all sample coastal water farms, while in contrast, anti-fouling management was adopted by all coastal water farms. Open sea cage farmers in Visakhapatnam also adopted anti-fouling measures such as cleaning and changing the cage nets at regular intervals. As most of the farms across sample locations were taking only one crop (6–8 months) per season, crop holidays were in place as a matter of course. However, nearly half of the practicing IMTA and coastal water cage farmers who raised Asian sea bass and red snapper for 9 months or more did not follow any crop holidays in between two consecutive crops.

## 4.4. Social indicators

The indicators of social sustainability in selected mariculture enterprises, as observed from the sample farms are presented in Table 4. Though inter-farm variations existed, the farms in general scored high on institutional linkage (IL) and social engagement (SE), as they maintained close linkages with research institutions, aquaculture development agencies of Union and State Governments, training organizations, farmers' associations/societies and non-governmental organizations in the area. They used such linkages mainly to acquire technological updates on farming, to gain access to financial, technical, and extension assistance, skill development through training programs, and to enhance their farm management skills. The indicators also suggested that mariculture has augmented employment and gender inclusion in the study areas. Employment estimates varied across enterprises, and locations, and ranged from 94 to 396 man-days/unit/crop. The highest average man-day requirement was for the IMTA (395.7 man-days/unit) and marine cage farms (321.4 man-days/unit) in Tamil Nadu, whereas coastal water IMTA in Karnataka (90.2 man-days/crop) and seaweed farming (98.7 man-days/crop) in Tamil Nadu scored low on employment. The results corresponding to crew insurance (CI) and social protection (SP) were nil in all sample farms across locations, suggesting wide gaps in the social dimensions of sustainability in sample farms. The farm units in Andhra Pradesh and Karnataka were, however, maintaining notably good measures to ensure crew safety at work like the use of floaters, life jackets, hand gloves, rubber shoes, etc.

## 4.5. Willingness to adopt sustainable practices in future

Apart from the current level of adoption of sustainable practices, the study also assessed the farmers' general inclination and the likelihood of adopting sustainable farming as well as readiness to implement standard risk-proofing solutions. The estimates of the relative importance index (RII) on the above two dimensions are presented in Tables 5, 6. They ranged from 0 to 1, and values closer to 1 indicated a greater orientation to adopt sustainable farming practices and risk solutions. The RII estimate of a particular parameter, however, cannot be compared across enterprises/locations, but only makes sense if interpreted in relation to that of other parameters. The results suggested that the farmers were positively oriented toward most of the sustainable farming practices irrespective of sample locations, except for a few specific aspects. For instance, the open sea cage farmers in Andhra Pradesh and Tamil Nadu; coastal water cage farmers in Kerala and Andhra Pradesh, as well as seaweed farmers in Tamil Nadu, were relatively less inclined to pay for certified farm inputs such as seed or feed. Similarly, the open sea cage farmers in Andhra Pradesh were particularly reluctant to extend crop holidays, beyond what is being practiced presently. The respondents, cutting across enterprises, also showed their general unwillingness to engage any third-party auditing agencies in their farms. Likewise, varying levels of readiness were exhibited for vertical integration of value chain activities, diversification/scale-up of existing farm activities, use of genetically improved fish species, development of linkage with local government agencies, and so on in the future. Among the risk-proofing solutions, the sample respondents were relatively less inclined to pay for/arrange for insurance cover and social security/welfare registration of farm crew. Readiness for registration of migrant laborers was also low across the board. Coastal water cage farmers from Kerala and Andhra Pradesh were notably averse to accessing any disease surveillance platforms. Nevertheless, future measures to strengthen labor safety measures, surveillance tools, use of weather alert platforms, measures to check for invasive biofoulers, etc. scored relatively high among the sample respondents, irrespective of the enterprises and farming locations. The statistical tests indicated reasonable levels of internal consistency in all samples as indicated by the respective estimates of Cronbach's alpha. The $\chi^2$ values from the Kruskal-Wallis test across indicators were insignificant in any of the cases. The results of Dunn's test on the pair-wise significance of indicators were performed, and are available upon request.

# 5. Discussion

## 5.1. Major gaps from the SI point of view

This section analyses the major gaps in the study areas, viewed through the prism of sustainable intensification, stressing its major pillars and dimensions. It has been observed that the sample farms constitute either individual family-operated units (mainly backwater cages and a few open sea cages or IMTA units), or a cluster of units jointly operated by SHGs or fisher societies. In general, all the enterprises examined were relatively labor-intensive, with family labor as a major source. A significant part of the labor is consumed for feeding and other routine management practices. Though a source of gainful employment for the farm families and local labor community, the higher labor requirement of these enterprises adds to the cost of production, thereby affecting input-use efficiency and profitability. The efficiency of the systems can be enhanced through the gradual introduction of cost-effective mechanization and automation solutions for routine management practices so that the labor thus released can be utilized for broad-basing and intensifying culture activities. Similarly, capital self-sufficiency was found to be low in several sample locations, which is to be read in conjunction with the abysmally low availability of institutional credit. This indicates the dependence of farmers on informal credit sources to meet capital and operational expenditure. Previous literature suggests that the rural non-institutional credit market is generally unorganized, exploitative, and devoid of transparency (Inoue, 2011; Parappurathu et al., 2019), often leading to a perpetual debt burden on the farming community. Enhancements in financial inclusion in coastal areas therefore can potentially improve access to capital, reduce capital costs and boost the entrepreneurial capacity of mariculture farmers. Another notable feature associated with mariculture farms in most of the study areas is the lack of any legally valid use rights for culture. This is mainly due to the regulatory vacuum on mariculture governance in the internal waters, territorial waters, or beyond, which constrains the local government institutions from taking appropriate actions to issue leases or licenses for culture in open-access water bodies. The lack of any serious conflicts with other users of internal and marine waters presently, given the early stage of mariculture development, is another reason for low concern about such legal rights. However, this is subject to change with the greater intensification of culture activities and will be more obvious in the open ocean where access rights are contentious and subject to intense debates (Percy et al., 2013; Cohen et al., 2019; Davies et al., 2019).

Both marine and coastal water cage farmers have reported using wild collected seed, which is notably on the flip side from the sustainability angle, as there is a severe shortage of cultured seeds. Lobster farming in Gujarat is a CBA enterprise with complete dependence on wild sources for seed, as commercial hatchery production facilities for lobsters are yet to be established. For most species, the local availability of hatchery-produced seed becomes a limiting factor often due to value chain constraints, leading to delays in the establishment of the crop. The need for the development of broodstock centers and hatcheries across the coastal belt is increasingly being felt, given the growing acceptance of mariculture among the prospective entrepreneurs

**TABLE 5** Estimates of Relative Importance Index (RII) indicating the willingness to embrace standard sustainable practices in the future by the sample respondents practicing the selected mariculture enterprises (over and above existing level).

| Indicators | Open sea cage farming | | | Coastal water cage farming | | | IMTA | | Seaweed farming |
|---|---|---|---|---|---|---|---|---|---|
| | Tamil Nadu | Andhra Pradesh | Gujarat | Karnataka | Kerala | Andhra Pradesh | Tamil Nadu | Karnataka | Tamil Nadu |
| Willingness to adopt and invest in new technology | 0.86 | 0.97 | 0.87 | 0.89 | 0.76 | 0.76 | 0.88 | 0.90 | 0.98 |
| Readiness to follow scientific farming practices through regular follow-up | 0.86 | 0.86 | 0.93 | 0.86 | 0.69 | 0.96 | 0.84 | 0.85 | 0.87 |
| Readiness to attend technical training/seminar/workshops | 0.70 | 0.86 | 0.97 | 0.84 | 0.74 | 0.88 | 0.98 | 0.95 | 0.89 |
| Willingness to pay for certified farm inputs (seed/feed) | 0.61 | 0.37 | 0.90 | 0.85 | 0.63 | 0.76 | 0.80 | 0.90 | 0.79 |
| Willingness to farm genetically improved species from recognized agencies | 0.56 | 0.83 | 0.87 | 0.81 | 0.63 | 0.96 | 0.66 | 0.90 | 0.66 |
| Willingness to perform water quality tests before each crop | 0.94 | 0.57 | 0.87 | 0.82 | 0.47 | 0.62 | 1.00 | 0.75 | 0.80 |
| Readiness to switch to green energy (solar/wind/other) | 0.72 | 0.77 | 0.80 | 0.89 | 0.67 | 0.94 | 0.86 | 1.00 | 0.80 |
| Readiness to extend crop holidays | 0.74 | 0.31 | 0.77 | 0.84 | 0.62 | 0.72 | 0.84 | 0.70 | 0.74 |
| Readiness to adopt Good Management Practices (GMPs) | 0.89 | 0.97 | 0.83 | 0.94 | 0.74 | 0.90 | 0.94 | 1.00 | 0.65 |
| Readiness to adopt farm hygiene/product safety measures | 0.88 | 0.74 | 0.83 | 0.87 | 0.65 | 0.88 | 0.86 | 1.00 | 0.80 |
| Readiness to link with farmer societies/SHGs/FPOs/Other | 0.89 | 0.94 | 0.73 | 0.86 | 0.42 | 0.76 | 0.80 | 0.95 | 0.82 |
| Readiness to link with local government bodies | 0.85 | 0.48 | 0.90 | 0.85 | 0.40 | 0.82 | 0.90 | 0.90 | 1.00 |
| Readiness to link with community organizations | 0.83 | 0.66 | 0.77 | 0.89 | 0.56 | 0.86 | 0.74 | 0.90 | 0.68 |
| Willing to act as a master trainer to promote successful technologies | 0.92 | 0.91 | 0.90 | 0.83 | 0.49 | 0.86 | 0.84 | 0.95 | 0.80 |
| Willingness for periodic farm auditing by a third-party agency | 0.45 | 0.46 | 0.57 | 0.65 | 0.49 | 0.24 | 0.54 | 0.75 | 0.67 |
| Likelihood to diversify farm activities in the near future | 0.84 | 0.54 | 0.83 | 0.96 | 0.62 | 0.86 | 0.72 | 0.95 | 0.87 |
| Likelihood to increase scale of farm production in the near future | 0.86 | 0.71 | 0.87 | 0.92 | 0.58 | 0.88 | 0.80 | 0.95 | 0.82 |
| Willingness for vertical integration (marketing/processing/other ventures) | 0.61 | 0.60 | 0.87 | 0.78 | 0.60 | 0.44 | 0.94 | 0.80 | 0.82 |
| Cronbach's alpha | 0.69 | 0.91 | 0.86 | 0.63 | 0.87 | 0.86 | 0.73 | 0.89 | 0.76 |
| $\chi^2$ (Kruskal-Wallis Test) | 16.9 (0.46) | 16.9 (0.45) | 16.5 (0.49) | 16.8 (0.46) | 16.9 (0.46) | 16.7 (0.47) | 16.8 (0.46) | 16.2 (0.50) | 16.7 (0.47) |
| Sample size | 20 | 7 | 14 | 34 | 30 | 10 | 10 | 4 | 30 |

RII >0.8 🟩 RII 0.6–0.8 🟩 RII 0.4–0.6 🟨 RII 0.2–0.4 🟧 RII <0.2 🟥

Figures in parentheses indicate the probability value of $\chi^2$ statistic; The RII estimate categories depicted in different colors do not convey any particular meaning, but were used to signify the relative willingness of the respondents w.r.t the selected indicators; The estimates may suffer from "free-rider problem" as their responses are independent of any costs associated with the adoption of the sustainable practices indicated.

**TABLE 6** Estimates of relative importance index (RII) indicating the readiness to adopt standard risk proofing mechanisms in the future by the sample respondents practicing the selected mariculture enterprises (over and above existing level).

| Indicators | Open sea cage farming | | | Coastal water cage farming | | | IMTA | | Seaweed farming |
|---|---|---|---|---|---|---|---|---|---|
| | Tamil Nadu | Andhra Pradesh | Gujarat | Karnataka | Kerala | Andhra Pradesh | Tamil Nadu | Karnataka | Tamil Nadu |
| Willingness to adopt labor safety measures on the farm | 0.93 | 0.57 | 0.80 | 0.89 | 0.58 | 0.76 | 0.94 | 0.85 | 0.92 |
| Readiness to use security/surveillance tools | 0.82 | 0.60 | 0.90 | 0.81 | 0.58 | 0.96 | 0.88 | 0.70 | 0.98 |
| Willingness to pay for aquaculture insurance | 0.85 | 0.54 | 0.70 | 0.87 | 0.60 | 0.88 | 0.80 | 0.80 | 0.85 |
| Willingness to pay for group insurance cover for farm crew/laborers | 0.74 | 0.54 | 0.73 | 0.72 | 0.78 | 0.96 | 0.82 | 0.75 | 0.80 |
| Readiness for social security/welfare registration for the farm crew | 0.74 | 0.66 | 0.73 | 0.75 | 0.51 | 0.74 | 0.70 | 0.75 | 0.70 |
| Readiness for registration of migrant laborers | 0.55 | 0.66 | 0.60 | 0.76 | 0.54 | 0.62 | 0.50 | 0.75 | 0.55 |
| Readiness to access weather alert platforms | 0.84 | 0.83 | 0.83 | 0.87 | 0.45 | 0.94 | 0.96 | 1.00 | 0.80 |
| Readiness to act on alerts on Harmful Algal Blooms (HAB) | 0.79 | 0.69 | 0.73 | 0.89 | 0.47 | 0.72 | 1.00 | 0.90 | 0.89 |
| Readiness to access disease surveillance platforms | 0.73 | 0.80 | 0.73 | 0.86 | 0.31 | 0.52 | 0.76 | 0.95 | 1.00 |
| Readiness to ensure check on invasive bio-foulers in cages/rafts | 0.76 | 1.00 | 0.77 | 0.87 | 0.65 | 0.90 | 0.98 | 0.90 | 0.93 |
| Cronbach's alpha | 0.77 | 0.95 | 0.77 | 0.76 | 0.80 | 0.74 | 0.74 | 0.89 | 0.75 |
| $\chi^2$ (Kruskal-Wallis test) | 8.9 (0.44) | 8.8 (0.44) | 8.4 (0.49) | 8.8 (0.45) | 8.9 (0.44) | 8.9 (0.44) | 9.0 (0.43) | 8.7 (0.46) | 8.9 (0.44) |
| Sample size | 20 | 7 | 14 | 34 | 30 | 10 | 10 | 4 | 30 |

RII >0.8 🟩 RII 0.6–0.8 ▨ RII 0.4–0.6 🟨 RII 0.2–0.4 🟧 RII <0.2 🟥

Figures in parentheses indicate the probability value of $\chi^2$ statistic. The RII estimate categories depicted in different colors do not convey any particular meaning, but were used to signify the relative willingness of the respondents w.r.t the selected indicators. The estimates may suffer from "free-rider problem" as their responses are independent of any costs associated with the adoption of the sustainable practices indicated.

and fisher folk community. A wide variety of aquaculture feed, mainly artificial floating pellet feeds are being used by the sample farm units. At the same time, a significant proportion of sample farmers also depend on low-value trash fish sourced from the wild as by-catch. The choice of feed depended considerably on the type of fish farmed, and the market availability of pellet feeds at affordable prices. For instance, farmers growing pompano mainly opted for pellet feeds throughout the culture duration, as raw fish is not a desirable option in such farms. However, those farmers using hatchery-based Asian sea bass and Orange-spotted grouper seeds administer artificial pellet feeds in the initial stages of the crop, before switching to raw fish subsequently. Farmers from almost all sample locations indicated that a shortage of good quality feed is a major constraint in mariculture, and excessive feed prices push the cost of production up. As in the case of the shrimp farming sector, private entrepreneurs in India presently have greater opportunities to capitalize on the growing demand for feeds and specialized growth promoters in the mariculture sector. There is also immense scope to diversify and broad-base value chains associated with mariculture farms to overcome their relative recentness. Most of the existing farms depend on limited formats of local markets with very few market linkages, as the results indicate. There is also a need to modernize the existing aqua-fish markets and minimize the prevalence of reported unfair marketing practices. Social dimensions of sustainability such as social engagement, gender inclusion, crew insurance, crew safety, social protection, etc. also need significant attention to ensure the long-term welfare of both the owner-operators as well as farm crew associated with mariculture units. However, much of the change is possible only through enhanced institutional and policy interventions over and above farm-level attention, given their overarching nature cutting across sectors and regions.

The sample units in general performed low on technical and environmental indicators. Major gaps were noticed in mechanization, use of renewable energy, disease, and hygiene management, farm surveillance, aeration management, anti-fouling, water quality monitoring, etc., with negative impacts on the environmental sustainability of the farms. Notably, most of the farms, except cage farms engaged in lobster fattening in Veraval (in Gujarat state), and coastal water cage farms in Kerala were predominantly observed to under-stock their farm units with fish seeds, leading to sub-optimal crop yields. Plugging this gap by enhancing seed availability and extension interventions can substantially improve the economic viability of the units. The profitability of farms at many locations was also found to be affected by several input-side constraints and other extraneous factors. For instance, the coastal water cage farmers in Andhra Pradesh indicated that delay in obtaining fish seeds on time resulted in the late start of culture activities thereby curtailing the culture period. Some farmers in the same location also indicated mortality due to wastewater infusion in the water body from neighboring industrial units. Yield enhancement, being one of the primary pillars of SI, thus needs concerted attention in all the study areas, and can be achieved through the optimal stocking of seeds, enhancing culture intensity through polyculture of suitable species, and the adoption of scientific management of various biotic and abiotic constraints. Some of the prospective interventions on the latter dimension include carrying capacity and water quality assessment at regular intervals, use of disease-free SPF seeds, surveillance mechanisms for disease incidence, adoption of aquatic animal health codes applicable for open water bodies, measures to prevent siltation and bio-fouling, checking incidence of invasive species, re-alignment of crop schedules to suit salinity and temperature of water body through regular monitoring, and so on (OIE, 2019; Fox et al., 2020; Wanja et al., 2020). IMTA, being a novel practice introduced recently in Tamil Nadu, has limited adoption presently. Nevertheless, enhanced growth and higher yields of the extractive species and the potential for mitigation of biofouling around the cages, it has considerable future scope in India. Similarly, the seaweed farming sector needs a greater supply of planting materials either through genetic improvement and mass multiplication programs or the introduction of suitable exotic species after due screening for any negative ecological consequences (Johnson et al., 2021).

## 5.2. Policy imperatives for bridging the gaps

Given the early stage of development, sustainability problems associated with the expansion of mariculture activities are yet to unfold fully in India. As obvious, the role of public policy is much more pronounced in ensuring the SI of mariculture compared to that of inland aquaculture. This is mainly because of the complexities associated with property rights, equity, and social justice; investment necessities for standardization of hatchery production and culture protocols of non-domesticated marine species, cumbersome management requirements in the marine environment, technological challenges associated with production scale-up and precision mariculture, as well as the emerging challenges posed by climate change and associated extreme weather events. The technical and human-resource prerequisites for empowering and enabling resource-poor coastal dwellers to take-up capital intensive mariculture activities are also high. The Government of India has recently floated ambitious programs to support prospective farming ventures, intending to provide the necessary logistic, funding, and policy support. However, there are glaring gaps that include the lack of a comprehensive mariculture policy at national and state levels and the lack of clarity on property rights in the open ocean and internal waters. Apart from these, executive and policy actions are needed to address the emerging requirements to enable the development of a self-sustaining mariculture sector in the country. Some of the specific recommendations in this regard include (i) development of marine spatial plans (MSP) for optimal allocation of available ocean space, (ii) introduction of legislations at appropriate levels to support leasing and licensing arrangements, (iii) measures to ensure adequate supply of seed and feed through channelizing public funding and by incentivising the private sector, (iv) strengthening of food safety and health management in mariculture farms, (v) developing mandatory guidelines on good farming practices (e.g., measures for anti-fouling, water quality monitoring, crop holiday management, safety and security measures, etc.) to obtain farm registration, (vi) enhancing multidisciplinary research on mariculture systems, (vii) bring about market reforms for the development of competitive value chains, (viii) introduction of specialized schemes to support auxiliary pre-requisites such as credit, insurance, and other support services, and (ix) promoting group farming, co-operative farming and farmer producer companies among mariculture farmers (Bostock et al., 2010; FAO, 2016; Gopalakrishnan et al., 2017, 2019). Governance of mariculture is equally convoluted, given the existence of diverse stakeholders with competing interests, besides the concerns about equity and the challenges of enforcement. There are innumerable debatable issues related to the ownership and operatorship formats (cooperative/corporate/private/other), engagement within the varied social and political realms, alignment with cross-cutting sectors, and so on, which need early resolution (Percy et al., 2013; Davies et al., 2019). Above all, there have to be appropriate institutions and governance arrangements in place to ensure that future expansion of mariculture development in the country is fully consistent with a precautionary approach to environmental sustainability and guided by Ecosystem Approach to Aquaculture (EAA) to ensure the resilience of interlinked social-ecological systems.

## 6. Conclusions

Though predominantly smallholder-centric, mariculture can be a potential future source of marine fish production in India. Over the past one and half decades, there have been notable achievements in terms of technological breakthroughs in breeding, seed production, and grow-out of marine finfish and shellfish species in artificial enclosures/structures, thereby aiding their profitable farming in the open sea as well as coastal and estuarine waters. Some of the potential enterprises for future scale-up include open sea cage farming, coastal water cage farming, seaweed farming, and integrated multi-trophic aquaculture, among others. This paper evaluates the present status of selected mariculture enterprises in their very cradles situated along India's east and west coasts, followed by a critical assessment of their future potential for sustainable intensification. The study follows the Principles-Criteria-Indicator (PCI) approach to assess the sustainability status and scope for intensification based on primary field data, pinning on a set of objectively measurable indicators on techno-economic, techno-environmental as well as social dimensions of sustainability. Further, the extent to which the sample respondents are willing to adopt sustainable farming practices as well as risk-proofing mechanisms on-farm, over and above the existing level is assessed using their responses to a set of selected questions on a five-point Likert scale. Of particular relevance for the above analysis include the quality of resource endowments, entrepreneurial readiness and capital availability, farming skills and technical prowess of the farmers, farm-level profitability, on-farm interventions to ensure environmental sustainability, community knowledge capital, backward and forward linkages w.r.t. input and product markets respectively, level of value chain integration, and so on. All the selected enterprises were assessed to be technically and economically viable in general; nevertheless, glaring gaps were evident on key indicators of sustainability such as the legitimacy of access over water bodies, use of quality seed and feed, institutional credit access, market access and fair marketing practices, optimal stocking density, mechanization, use of renewable energy, adoption of environment-friendly culture practices, farm surveillance, crew safety, and social protection. The study takes due cognizance of the fact that the development of several auxiliary economic enterprises, directly or indirectly related to mariculture, and their assimilation and integration into the diversified coastal economy are necessary to realize transformational changes. The findings underscore the need for greater technological, policy, and institutional intercessions, as India gears toward the sustainable and inclusive expansion of its blue economy in the years to come.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## Author contributions

SPar: conceptualization, methodology, investigation, and original draft preparation. MM, CJ, JB, and AA: investigation, data, and reviewing and editing. CR: conceptualization and methodology. PL and NA: data and reviewing and editing. SPad: study area map and reviewing and editing. SG, DD, SM, GR, and SV: investigation and review and editing. BI, SR, RN, AG, and PC: conceptualization, reviewing, and overall guidance. All authors contributed to the article and approved the submitted version.

## Funding

The authors gratefully acknowledge the financial support obtained from the Indian Council of Agricultural Research (through ICAR National Network Project No. #1013464 entitled, Production Systems, Agribusiness, and Institutions—Component 1: Impact of Agricultural Technology hosted by ICAR-NIAP, New Delhi).

## Acknowledgments

The insightful comments and overall guidance provided by Dr. Prathap Singh Birthal, Director, NIAP and Dr. J. Jayasankar, Head, Fishery Resource Assessment, Economics and Extension Division of ICAR-CMFRI is thankfully acknowledged. The support provided by Dr. Vinaya Kumar Vase in data collection, review, and editing of the manuscript is sincerely appreciated. The technical assistance from Dr. Suresh Kumar Mojjada in validating some of the results is also appreciated. We place on record, our sincere gratitude to all the mariculture farmers, entrepreneurs, experts and other government officials who provided valuable information for use in the manuscript through primary surveys and direct/telephonic interviews. The views expressed are personal.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer KP declared a past co-authorship with the author SP to the handling editor.

## Publisher's note

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1078314/full#supplementary-material

## References

Alagarswami, K. (1974). "Development of pearl culture in India and scope for a pearl culture industry," in *Proceedings of the Group Discussion On Pearl Culture,* ed R. V. Nair (Cochin: CMFRI), 4–19.

Anuraj, A., S. B., Loka, J., Ignatius, B., Santhosh, B., Ramudu, K. R., et al. (2021). Induced breeding and larval rearing of vermiculated spinefoot, Siganus vermiculatus (Valenciennes, 1835) in indoor conditions. *Aquaculture* 539, 736600. doi: 10.1016/j.aquaculture.2021.736600

Appukuttan, K. K. (1980). Culture of brown mussel *Perna indica* at Vizhinjam. *Mar. Fish. Info. Serv.* 16, 11–13.

Arasu, A. R. T., Kailasam, M., and Sundaray, J. K. (2009). *Asian Seabass, Fish Seed Production and Culture.* CIBA Special Publication 42. Chennai: Central Institute of Brackishwater Aquaculture, 158.

Arquitt, S., Honggang, X., and Johnston, R. (2005). A system dynamics analysis of boom and bust in the shrimp aquaculture industry. *Syst. Dyn. Rev.* 21, 305–324. doi: 10.1002/sdr.313

Aswathy, N., Joseph, I., Ignatius, B., and Joseph, S. (2020). *Economic Viability of Cage Fish Farming in India.* CMFRI Special Publication 134. Kochi: Central Marine Fisheries Research Institute.

Ayyappan, S., Jena, J. K., Lakra, W. S., Gopal, T. K. S., Gopalakrishnan, A., Vass, K. K., et al. (2015). "Fisheries sciences," in *100 Years of Agricultural Sciences in India*, ed R. B. Singh (New Delhi: National Academy of Agricultural Sciences).

Balasubramanian, C. P., Mhaskar, S. S., Sukumaran, K., Panigrahi, A., Vasagam, K., Kumararaja, P., et al. (2018). Development of integrated multi-trophic aquaculture (IMTA) for tropical brackishwater species in Sindhudurg district, Maharashtra, west coast of India. *Ind. J. Fish.* 65, 59–64. doi: 10.21077/ijf.2018.65.1.70128-10

Barrington, K., Chopin, T., and Robinson, S. (2009). "Integrated multi-trophic aquaculture (IMTA) in marine temperate waters," in *Integrated Mariculture: A Global Review*, ed D. Soto. FAO Fisheries and, Aquaculture Technical Paper 529 (Rome: FAO), 7–46.

Bavinck, M., Berkes, F., Charles, A., Dias, A. C. E., Doubleday, N., Nayak, P., et al. (2017). The impact of coastal grabbing on community conservation—a global reconnaissance. *Mar. Stud.* 16, 8. doi: 10.1186/s40152-017-0062-8

Belton, B., and Little, D. C. (2008). The development of aquaculture in Central Thailand : domestic demand versus export-led production. *J. Agric.* 8, 123–143. doi: 10.1111/j.1471-0366.2007.00165.x

Belton, B., Little, D. C., Zhang, W., Edwards, P., Skladany, M., and Thilsted, S. H. (2020). Farming fish in the sea will not nourish the world. *Nat. Commun.* 11, 5804. doi: 10.1038/s41467-020-19679-9

Biswas, G., Kumar, P., Kailasam, M., Ghoshal, T. K., Bera, A., and Vijayan, K. K. (2019). "Application of integrated multi-trophic aquaculture (IMTA) concept in brackishwater ecosystem: the first exploratory trial in the Sundarban, India," in *BRAQCON 2019: World Brackishwater Aquaculture Conference*, Special Issue No. 86. eds K. P. Jithendran, R. Saraswathy, C. P. Balasubramanian, K. P. Kumaraguru Vasagam, V. Jayasankar, R. Raghavan, et al. (FL: Coconut Creek), 49–55. doi: 10.2112/SI86-007.1

Bostock, J., McAndrew, B., Richards, R., Jauncy, K., Telfer, T., Lorenzen, K., et al. (2010). Aquaculture: global status and trends. *Philos. Trans. R. Soc. B* 365, 2897–2912. doi: 10.1098/rstb.2010.0170

Boyd, C. E., D'Abramo, L. R., Glencross, B. D., Huyben, D. C., Juarez, L. M., Lockwood, G. S., et al. (2020). Achieving sustainable aquaculture: historical and current perspectives and future needs and challenges. *J. World Aqua. Soc.* 51, 578–633. doi: 10.1111/jwas.12714

Buck, B. H. and Langan, R. (eds.) (2017). *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*. Geneva: Springer Nature. doi: 10.1007/978-3-319-51159-7

Cao, L., Diana, J. S., Keoleian, G. A., and Lai, Q. (2011). Life cycle assessment of Chinese shrimp farming systems targeted for export and domestic sales. *Environ. Sci. Technol.* 45, 6531–6538. doi: 10.1021/es104058z

Carballeira Braña, C. B., Cerbule, K., Senff, P., and Stolz, I. K. (2021). Towards environmental sustainability in marine finfish aquaculture. *Front. Mar. Sci.* 8, 666662. doi: 10.3389/fmars.2021.666662

Chakraborty, K., Vijayagopal, P., and Gopalakrishnan, A. (2018). Nutraceutical products from seaweeds-wonder herbs of the oceans. *Mar. Fish. Info. Serv.* 237, 7–12.

Chopin, T., Robinson, S. M. C., Troell, M., Neori, A., Buschmann, A. H., and Fang, J. (2008). "Multitrophic integration for sustainable marine aquaculture," in *The Encyclopedia Ecolological Engineering, Vol 3*, ed S. E. Jørgensen and B. D. Fath (Oxford: Elsevier), 2463–2475. doi: 10.1016/B978-008045405-4.00065-3

Clawson, G., Kuempel, C. D., Frazier, M., Blasco, G., Cottrell, R. S., Froehlich, H. E., et al. (2022). Mapping the distribution of global mariculture production. *Aquaculture* 553, 738066. doi: 10.1016/j.aquaculture.2022.738066

Cohen, P. J., Allison, E. H., Andrew, N. L., Cinner, J., Evans, L. S., Fabinyi, M., et al (2019). Securing a just space for small-scale fisheries in the blue economy. *Front. Mar. Sci.* 6, 171. doi: 10.3389/fmars.2019.00171

Cossutta, M., Pholboon, S., McKechnie, J., and Sumner, M. (2022). Techno-economic and environmental analysis of community energy management for peak shaving. *Energy Conv Manage.* 251, 114900. doi: 10.1016/j.enconman.2021.114900

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M. A., Free, C. M., Froehlich, H. E., et al. (2020). The future of food from the sea. *Nature* 588, 95–100. doi: 10.1038/s41586-020-2616-y

Cotas, J., Leandro, A., Pacheco, D., Gonçalves, A. M. M., and Pereira, L. A. (2020). Comprehensive review of the nutraceutical and therapeutic applications of Red Seaweeds (Rhodophyta). *Life (Basel)* 10, 19. doi: 10.3390/life10030019

Davies, I. P., Carranza, V., Froehlich, H. E., Gentry, R. R., Kareiva, P., and Halpern, B. S. (2019). Governance of marine aquaculture: Pitfalls, potential, and pathways forward. *Mar. Pol.* 104, 29–36. doi: 10.1016/j.marpol.2019.02.054

Divu, D. N., Mojjada, S. K., Pokkathappada, A. A., Sukhdhane, K., Menon, M., Mojjada, R. K., et al. (2020). Decision-making framework for identifying best suitable mariculture sites along north-east coast of Arabian Sea, India: a preliminary GIS-MCE based modelling approach. *J. Clean Prod.* 284, 124760. doi: 10.1016/j.jclepro.2020.124760

Edwards, P., Zhang, W., Belton, B., and Little, D. C. (2019). Misunderstandings, myths, and mantras in aquaculture: its contribution to world food supplies has been systematically over-reported. *Mar. Pol.* 106, 103547. doi: 10.1016/j.marpol.2019.103547

European Commission (2001). *A Framework for Indicators for the Economic and Social Dimension of Sustainable Agriculture and Rural Development*. Brussels: EC.

FAO (2011). *Indicators for the Sustainable Development of Finfish Mediterranean Aquaculture: Highlights From the InDAM Project. Studies and Reviews. General Fisheries Commission for the Mediterranean. No.* 90. Rome: Food and Agricultural Organization of the United Nations.

FAO (2016). "Sustainable intensification of aquaculture in the Asia-Pacific region," in *Documentation of Successful Practices,* eds W. Miao and K. K. Lal (Bangkok: Food and Agricultural Organization of the United Nations).

Fezzardi, D., Massa, F., Àvila-Zaragoza, P., Rad, F., Yuzel-Gier, G., Deniz, H., et al. (2013). *Indicators for Sustainable Aquaculture in Mediterranean and Black Sea Countries. Guide for the Use of Indicators to Monitor Sustainable Development of Aquaculture, Studies and Reviews, No. 93.* Rome: UNFAO.

Fore, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., Dempster, T., et al. (2018). Precision farming: a new framework to improve production in aquaculture. *Biosyst. Eng.* 173, 176–193. doi: 10.1016/j.biosystemseng.2017.10.014

Fox, M., Christley, R., Lupo, C., Morre, H., Service, S., and Campbell, K. (2020). Preventing and mitigating farmed bivalve disease: a Northern Ireland case study. *Aquac. Int.* 28, 2397–2417. doi: 10.1007/s10499-020-00597-y

Garnett, T., Applebey, M. C., Balmford, A., Bateman, J., Benton, G., Bloomer, P., et al. (2013). Sustainable intensification in agriculture: premises and policies. *Science* 341, 33–34. doi: 10.1126/science.1234485

Gentry, R. R., Froehlich, H. E., Grimm, D., Kereiva, P., Parke, M., Rust, M., et al. (2017). Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* 1, 1317–1324. doi: 10.1038/s41559-017-0257-9

Gopakumar, G., Nair, K. R. M., and Kripa, V. (2007). "Mariculture research in India—status, constraints and prospects," in *Status and Perspectives in Marine Fisheries Research in India*, eds M. J. Modayil and N. G. K. Pillai (Kochi: CMFRI Diamond Jubilee Publication, Central Marine Fisheries Research Institute), 316–361.

Gopalakrishnan, A., Ignatius, B., and George, G. (2017). India's largest fisheries research body turns 70-CMFRI's legacy and a few recent achievements. *Fish. Chim.* 37, 38–44.

Gopalakrishnan, A., Kirubagaran, R., John, G., Ponniah, A. G., Gopakumar, G., Mohamed, K. S., et al. (2019). *Draft National Mariculture Policy 2019, Report of the Committee Constituted by the National Fisheries Development Board.* CMFRI Mar. Fish. Pol. Ser. No. 17/2020. New Delhi: Ministry of Fisheries, Animal Husbandry and Dairying, Government of India.

Gopalakrishnan, A., Ravishankar, C. N., Pravin, P., and Jena, J. K. (2020). *ICAR-Technologies: High-Value Nutraceutical and Nutritional Products From Seaweeds.* New Delhi: Indian Council of Agricultural Research.

Government of India (GoI) (2017). *National Policy on Marine Fisheries.* New Delhi: Ministry of Agriculture and Farmers Welfare, Government of India.

Government of India (GoI) (2019). *Report of Blue Economy Working Group-3, Fisheries, Aquaculture and Fish Processing.* New Delhi: Economic Advisory Council to the Prime Minister of India, Government of India.

Grealis, E., Hynes, S., O'Donoghue, C., Vega, A., and Osch, S. V. (2017). The economic impact of aquaculture expansion: an input-output approach. *Mar. Pol.* 81, 29–36. doi: 10.1016/j.marpol.2017.03.014

Henriksson, P. J. G., Belton, B., Murshed-e-Jahan, K., and Rico, A. (2018). Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment. *PNAS* 115, 2958–2963. doi: 10.1073/pnas.1716530115

Inoue, T. (2011). "Financial inclusion and poverty alleviation in India: an empirical analysis using state-wise data," in *Inclusiveness in India: A Strategy for Growth and Equality, IDE-JETRO Series*, ed S. Hirashima, H. Oda, and Y. Tsujitha (London: Palgrave Mcmillan). doi: 10.1057/9780230304956_4

Jena, J. K., Gopalakrishnan, A., Ravisankar, C. N., Lal, K. K., Das, B. K., Das, P. C., et al. (2022). "Achievements in fisheries and aquaculture in independent India," in *Indian Agriculture after Independence*, eds H. Pathak, J. P. Mishra and T. Mohapatra (New Delhi: Indian Council of Agricultural Research), 426.

Johnson, B., Divu, D., Jayasankar, R., Ranjith, L., Dash, G., Megarajan, S., et al. (2020). Preliminary estimates of potential areas for seaweed farming along the Indian coast. *Mar. Fish. Inf. Serv. Ser.* 246, 14–28.

Johnson, B., and Ignatius, B. (2020). Seaweed farming in India: progress and prospects. *Ind. Farm.* 70, 42–45.

Johnson, B., Jayakumar, A., Abdul Nazar, A. K., Tamilmani, G., Sakthivel, M., Rameshkumar, P., et al. (2021). "Climate resilient mariculture technologies for food and nutritional security," in *Exploring Synergies and Trade-offs Between Climate Change and the Sustainable Development Goals,* ed V. Venkatramanan (Berlin: Springer Nature). doi: 10.1007/978-981-15-7301-9_4

Johnson, B., Narayanakumar, R., Abdul Nazar, A. K., Kaladharan, P., and Gopakumar, G. (2017). Economic analysis of farming and wild collection of seaweeds in Ramanathapuram District, Tamil Nadu. *Ind. J. Fish.* 64, 94–99. doi: 10.21077/ijf.2017.64.4.61828-13

Kaladharan, P., Vijayakumaran, K., and and, Chennubhotla, V. S. K. (1996). Optimization of certain physical parameters for the mariculture of *Gracilaria edulis* (Gmelin) Silva in Minicoy lagoon (*Luccadive Archipelago*). *Aquaculture* 139, 265–270. doi: 10.1016/0044-8486(95)01160-9

Kaliaperumal, N., and Kalimuthu, S. (1997). Seaweed potential and its exploitation in India. *Seaweed Res. Util.* 19, 33–40.

Kobos, P. H., Drennen, T. E., Outkin, A. S., Webb, E. K., Paap, S. M., and Wiryadinata, S. (2020). Techn-economic analysis, best practices and assessment tools. *Sandia Rep. California* 2020, 94550. doi: 10.2172/1738878

Krishnan, M., and Narayanakumar, R. (2013). *Social and Economic Dimensions of Carrageenan Seaweed Farming.* FAO Fisheries and Aquaculture Technical Paper 580. Rome: FAO, 163–184.

Kuriakose, P. S. (1980). "Opensea raft culture of green mussel at Calicut," in *Coastal Aquaculture: Mussel Farming-Progress and Prospects*, eds K. N. Nayar, S. Mahadevan, K. Alagarswami, and P. T. Meenakshisundaram (Cochin: Bull. Cent. Mar. Fish. Res. Inst).

Little, D. C., Murray, F. J., Leschen, W., and Waley, D. (2013). "Socio-economic factors affecting aquaculture site selection and carrying capacity," in *Site Selection and Carrying Capacities for Inland and Coastal Aquaculture*, eds L. G. Ross, T. C. Telfer, L. Falconer, D. Soto and J. Aguilar-Manjarrez. FAO/Institute of Aquaculture, University of Stirling, Expert Workshop, 6-8 December 2010. Stirling, the United Kingdom of Great Britain and Northern Ireland. FAO Fisheries and Aquaculture Proceedings No. 21 (Rome: FAO), 282.

Little, D. C., Young, J. A., Zhang, W., Newton, R. W., Mamun, A. A., and Murray, F. J. (2018). Sustainable intensification of aquaculture value chains between Asia and Europe: a framework for understanding impacts and challenges. *Aquaculture* 493, 338–354. doi: 10.1016/j.aquaculture.2017.12.033

Liu, W. H., and Ou, C. H. (2007). A comparative analysis of sustainable fishery development indicator system in Australia and Canada. *Sustain. Dev.* 15, 28–40. doi: 10.1002/sd.291

Mantri, V. A., Dineshkumar, R., Yadav, A., Easwaran, K., Shanmugam, M., and Gajaria, T. K. (2022a). Projections for profitability assessment parameters under short-term, medium-term and long-term evaluation for three farming techniques of *Kappaphycus alvarezii* along eastern coast of India. *Aquaculture* 551, 737912. doi: 10.1016/j.aquaculture.2022.737912

Mantri, V. A., Dineshkumar, R., Yadav, A., Veeragurunathan, V., Ganesan, M., Eswaran, K., et al. (2022b). How profitability assessment parameters score under large-scale commercial cultivation of different agarophyte seaweeds along the south-eastern coast of India. *Aquac. Int.* 30, 1505–25. doi: 10.1007/s10499-022-00866-y

Mohamed, K. S., Kripa, V., Asokan, P. K., Sasikumar, G., Venkatesan, V., Jenni, B., et al. (2016). "Development of bivalve farming as a source of income generation for women's self-help groups in costal India," in *Sustainable Intensification of Aquaculture in the Asia-Pacific Region. Documentation of Successful Practices*, eds W. Miao and K. K. Lal (Bangkok: UN FAO).

National Fisheries Development Board (NFDB) (2018). *Guidelines for Sea Cage Farming in India: Towards Blue Revolution*. New Delhi: Ministry of Agriculture and Farmers Welfare, Government of India.

OIE (2019). *The Aquatic Animal Health Code, Twenty-Second Edition.* Paris: World Organization for Animal Health. Available online at: http://www.oie.int/standard-setting/aquatic-code/acces-online/ (accessed March 20, 2021).

Parappurathu, S., George, G., Narayanakumar, R., Aswathy, N., Ramachandran, C., and Gopalakrishnan, A. (2017). Priorities and strategies to boost incomes of marine fisher folk in India. *Agric. Econ. Res. Rev.* 30, 205–216. doi: 10.5958/0974-0279.2017.00035.0

Parappurathu, S., Ramachandran, C., Baiju, K. K., and Xavier, A. K. (2019). Formal versus informal: insights into the credit transactions of small-scale fishers along the south west coast of India. *Mar. Pol.* 103, 101–122. doi: 10.1016/j.marpol.2019.02.032

Parappurathu, S., Sanil, N. K., Asokan, P. K., Sharma, S. R. K., Pradeep, M. A., Padua, S., et al. (2021). Green mussel (*Perna viridis* L.) farming in India: an analysis of major growth milestones, recent decline due to disease incidence, and prospects for revival. *Aquac. Int.* 29, 1813–1828. doi: 10.1007/s10499-021-00716-3

Parris, T. M., and Kates, R. W. (2003). Characterizing and measuring sustainable development. *Annu. Rev. Environ. Resour.* 28, 559–586. doi: 10.1146/annurev.energy.28.050302.105551

Percy, D. R., Hishamunda, N., and Kuemlangan, B. (2013). "Governance in marine aquaculture: the legal dimension," in *Expanding Mariculture Farther Offshore: Technical, Environmental, Spatial and Governance Challenges*, eds A. Lovatelli, J. Aguilar-Manjarrez and D. Soto. FAO Technical Workshop, 22–25 March 2010, Orbetello, Italy. FAO Fisheries and Aquaculture Proceedings No. 24. Rome: FAO, 245–262.

Pretty, J. (1997). The sustainable intensification of agriculture. *Nat. Res. For.* 21, 247–256. doi: 10.1111/j.1477-8947.1997.tb00699.x

Primavera, J. H. (1997). Socio-economic impacts of shrimp culture. *Aqua. Res.* 28, 815–827. doi: 10.1111/j.1365-2109.1997.tb01006.x

Qasim, S. Z., Parulekar, A. H., Harkantra, S. N., Ansari, Z. A., and Nair, A. (1977). Aquaculture of green mussel *Mytilus viridis* L. cultivation on ropes from floating rafts. *Indian J. Mar. Sci.* 4, 189–197.

Ranjan, R., Muktha, M., Ghosh, S., Gopalakrishnan, A., Gopakumar, G., and Joseph, I. (2017). *Prioritized Species for Mariculture in India.* Kochi: ICAR-Central Marine Fisheries Research Institute.

Rao, G. S., Joseph, I., Philipose, K. K., and Mojjada, S. K. (2013). *Cage Aquaculture in India*. Kochi: Central Marine Fisheries Research Institute.

Rao, P. V. S., and Mantri, V. A. (2006). Indian seaweed resources and sustainable utilization: scenario at the dawn of a new century. *Curr. Sci.* 91, 164–174.

Rey-Valette, H., Clement, O., Aubin, J., Mathe, S., Chia, E., Legendre, M., et al. (2008). *Guide to the Co-construction of Sustainable Development Indicators in Aquaculture*. Montpellier: EVAD.

Rey-Valette, H., Clement, O., Aubin, J., Mathe, S., Chia, E., Legendre, M., et al. (2010). "An approach to co-construct sustainable development indicators in aquaculture," in *IIFET 2010* (Montpellier, France).

Salunke, M., Kalyankar, A., Khedkar, C. D., Shingare, M., and Khedkar, G. D. (2020). A review on shrimp aquaculture in India: historical perspective, constraints, status and future implications for impacts on aquatic ecosystem and biodiversity. *Rev. Fish. Sci. Aquac*. 28, 283–302. doi: 10.1080/23308249.2020.1723058

Seung, C. K., and Kim, D.-H. (2020). Examining supply chain for seafood industries using structural path analysis. *Sustainability* 12, 2061. doi: 10.3390/su12052061

Silas, E. G., and Kalimuthu, S. (1987). Commercial exploitation of seaweeds in India. *CMFRI Bull.* 41, 55–59.

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., and Glover, J. (2017). Measuring sustainable intensification in smallholder agro-ecosystems: a review. *Glob. Food Sec.* 12, 127–138. doi: 10.1016/j.gfs.2016.11.002

Stockstad, E. (2020). Tomorrow's catch. *Science* 370, 902–905. doi: 10.1126/science.370.6519.902

Suresh Babu, P. P., Anuraj, A., Shilta, M. T., Asokan, P. K., Vinod, K., Praveen, N. D., et al. (2022). Broodstock development, breeding and larval rearing of *Acanthopagrus berda* (Forsskal, 1775), a suitable species for farming in tropical waters. *Aquacult. Res.* 53, 6439–6453. doi: 10.1111/are.16114

Thivy, F. (1964). Marine algal cultivation. *Salt Res. Ind.* 1, 23–28. doi: 10.1007/BF00043738

Troell, M., Jonell, M., and Henriksson, P. J. G. (2017). Ocean space for seafood. *Nat. Ecol. Evol.* 1, 1224–1225. doi: 10.1038/s41559-017-0304-6

Valenti, W. C., Kimpara, J. M., Preto, B. L., and Moraes-Valenti, P. (2018). Indicators of sustainability to assess aquaculture systems. *Ecol. Ind.* 88, 402–413. doi: 10.1016/j.ecolind.2017.12.068

Wan, Z., and Liu, H. (2010). "On environmental impact assessment (EIA) of technology," in *Proceedings of the 2010 International Conference of Information Science and Management Engineering*, 450–452. doi: 10.1109/ISME.2010.241

Wang, C., Li, Z., Wang, T., Xu, X., Zhang, X., and Li, D. (2021). Intelligent fish farm: the future of aquaculture. *Aquac. Int*. 29, 2681–2711. doi: 10.1007/s10499-021-00773-8

Wanja, D. W., Mbuthia, P. G., Waruiru, R. M., Mwadime, J. M., Bebora, L. C., Nyaga, P. N., et al. (2020). Fish husbandry practices and water quality in central Kenya: potential risk factors for fish mortality and infectious diseases. *Vet. Med. Int* 2020, 6839354. doi: 10.1155/2020/6839354

World Bank and United Nations Department of Economic and Social Affairs (UN-DESA) (2017). *The Potential of the Blue Economy: Increasing Long-Term Benefits of the Sustainable Use of Marine Resources for Small Island Developing States and Coastal Least Developed Countries*. Washington DC: World Bank.

# Appendix

**TABLE A1** Sampling framework for primary data collection in selected coastal states of India, 2022.

| State | District | Location | Number sample respondents under | | | |
|---|---|---|---|---|---|---|
| | | | Marine cage farming | Coastal water cage farming | IMTA | Seaweed farming |
| Andhra Pradesh | Visakhapatnam | Visakhapatnam | 07 | | | |
| | Krishna | Lakshmipuram | | 03 | | |
| | | Pedapalem | | 07 | | |
| Tamil Nadu | Ramanathapuram | Kalaimangundu | 07 | | | |
| | | Chinnapalam | 04 | | | |
| | | Thankachimadam | 03 | | | |
| | | Kundhukal | 06 | | | |
| | | Mandapam | | | 10 | 25 |
| | | Rameswaram | | | | 05 |
| Kerala | Ernakulam | Gothuruthu | | 05 | | |
| | Alappuzha | Thrikkunnapuzha | | 08 | | |
| | | Arattupuzha | | 07 | | |
| | Kollam | Kollam | | 10 | | |
| Karnataka | Uttara Kannada | Karwar | | 08 | | |
| | | Kumta | | 07 | | |
| | | Bhatkal | | 05 | | |
| | Udupi | Uppunda | | 04 | | |
| | | Byndoor | | 04 | 04 | |
| | | Kundapura | | 06 | | |
| Gujarat | Gir Somnath | Veraval | 4 | | | |
| | Porbandar | Porbandar | 2 | | | |
| | Kutch | Kutch | 4 | | | |
| Diu | Diu | Diu | 4 | | | |
| All | | | 41 | 74 | 14 | 30 |

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 04 May 2023
DOI 10.3389/fsufs.2023.966376

Check for updates

OPEN ACCESS

EDITED BY
Sendhil R,
Pondicherry University, India

REVIEWED BY
Md Abdur Rouf Sarkar,
Bangladesh Rice Research Institute, Bangladesh
Margiana Petersen-Rockney,
University of California, Berkeley, United States

*CORRESPONDENCE
Ravishankar Manickam
✉ ravi.manickam@worldveg.org

RECEIVED 10 June 2022
ACCEPTED 14 April 2023
PUBLISHED 04 May 2023

CITATION
Manickam R, Kaur DP, Vemula A, Rathore A, Unkovich M, Bellotti W, Kumar A, Gorai B and Madhavan Nair R (2023) Diversifying vegetable production systems for improving the livelihood of resource poor farmers on the East Indian Plateau.
*Front. Sustain. Food Syst.* 7:966376.
doi: 10.3389/fsufs.2023.966376

# Diversifying vegetable production systems for improving the livelihood of resource poor farmers on the East Indian Plateau

Ravishankar Manickam[1]*, Devender Pal Kaur[1], Anilkumar Vemula[2], Abhishek Rathore[2], Murray Unkovich[3], William Bellotti[4], Ashok Kumar[5,6], Bapi Gorai[5,6] and Ramakrishnan Madhavan Nair[1]

[1]World Vegetable Center, South Asia/Central Asia, ICRISAT Campus, Hyderabad, Telangana, India, [2]International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, Telangana, India, [3]School of Agriculture, Food and Wine, The University of Adelaide, Glen Osmond, SA, Australia, [4]Global Change Institute, The University of Queensland, St Lucia, QLD, Australia, [5]Professional Assistance for Development Action (PRADAN), Ranchi, Jharkhand, India, [6]TRIF-Transforming Rural India Foundation, Ranchi, Jharkhand, India

Failure of the rice crop, or low rice yield has dire consequences for rice-dependent households, including food insecurity and malnutrition, for India's poorest farmers in the East Indian Plateau region. Crop diversification could reduce the risks of rice production from the vagaries of rainfall and provide cash income which is not generated from subsistence rice. Being the primary household laborers women bear the brunt of these difficult conditions in patriarchal societies. For this reason we engaged with the women farmers in Bokaro and West Singhbhum in the State of Jharkhand, and Purulia in West Bengal who participated in experiments conducted with vegetable crops and legumes in the upland and medium uplands where the traditional crop is broadcasted paddy rice. We explored four different vegetable systems, (i) cucurbits (rainy/*kharif*) (season—June to September), (ii) growing tomatoes in the "off season" (rainy season—July to October), (iii) growing legume crops in rotation with direct sown rice (dry/rabi season—November to January), and (iv) intercropping beans with maize (rainy season—June to September). The results showed that all the above crops proved much better in terms of income to the farmers, return per person day, although the input cost varied it was higher with the new systems explored. The research with the small-holding women farmers enabled them to try new options and make informed decisions about these opportunities. This study showed that farmers can increase crop diversity and expand the area sown to non-paddy crops. The farmers are now looking for new crops where the demand exceeds the supply. Importantly this study has demonstrated that the direct involvement of communities' in research enables the farmers to sustainability explore solutions to the future problems with limited support from the external agencies.

KEYWORDS

**cropping system, legumes, paddy, off-season, intercropping, citizen science**

## Introduction

The largest concentration of people living in poverty in India are on the East India Plateau (EIP, Mitra, 2017). Here, in the State of Jharkhand, the Multidimensional Poverty Index is 0.44 compared to 0.28 for India overall and a staggering 75% of Jharkhand citizens live in poverty. It is no coincidence that this region is also home to many indigenous communities and to social unrest, due in part to Naxalite-Maoist insurgency (Dixit, 2010; Kumar, 2015) fed by marginalized, disenfranchised indigenous rural poor (Shah, 2007; Gomes, 2015). Most villagers on the EIP are food insecure with only 50–60% of their food grain requirement being met through on-farm production. This results in emigration by family members, particularly young males, causing on-farm labor shortages and social upheaval (Shah, 2006). These drivers contribute to widespread malnutrition, low literacy, particularly among girls, and limited access to medical services due to low household disposable income. Women play a central role in rural life on the EIP, not only do women carry the unborn child and breast feed newborn, they are the primary labor in agriculture, prepare family meals, grow nutrient dense food (vegetables, fruit, small livestock) and generate cash income.

India as a whole is characterized by sharp gender disparities and all the tribal societies in the study area are patriarchal with males making decisions about farming activities (Das and Tarai, 2011), but for these to be carried out by women who have little say in farm management even though they do most of the tedious farm work, cook for the family, clean the house and look after the children (Farnworth and Hutchings, 2009). Despite several economic, political and social changes, women are still far behind and held back by growing food rather than cash crops (Bhasin, 2007). There is widespread malnutrition, low literacy, particularly among girls, and limited access to medical services due to low household disposable income. Tribal women are particularly vulnerable to malnutrition (Kshatriya and Acharya, 2016). Despite their central role, gender inequality and discrimination leave many women disempowered and many now regard the empowerment of women as the key to improving nutrition (Debnath and Bhattacharjee, 2016), the largest contributor to poverty in the region.

The East Indian Plateau comprises much of the state of Jharkhand and parts of adjoining West Bengal, Bihar and Orissa. The region is characterized by high but variable rainfall (1,100–1,600 mm, 80% June–September), with frequent and sometimes long dry spells within the monsoon, little irrigation (~8% of area), high runoff and soil erosion, terraced mono-cropped paddy lands and subsistence agriculture. The main monsoon (*kharif*) crop is rice (overwhelmingly so for the poorer farmers), with generally very small areas of pulses, oilseeds and maize. Where *rabi* (post monsoon) crops are grown, they are typically fully irrigated crops of rice, vegetables, wheat, pulses and oilseeds. However, *rabi* cropping is very much limited by a lack of irrigation resources and by uncontrolled grazing by village cattle and goats and rainfed *rabi* crop yields are generally low (rice <2 t/ha, pulses <0.5 t/ha).

Historically rice is grown in the lowest parts of the landscape, but with increasing population pressure much of the original hillslopes have also been terraced and bunded over time to create medium-lowlands and medium-uplands for rice growing (Cornish et al., 2015) and up to 80% of the rice area is terraced and bunded "medium uplands." However, uplands are often degraded and make little contribution to overall productivity. Failure of the rice crop, or low rice yield can have dire consequences for households, including food insecurity, malnutrition and distressed migration of men, to look for employment opportunities elsewhere (Keshri and Bhagat, 2012). There is little mechanization on the EIP, seeds of crops are generally hand-broadcast, weeds are removed by hand, and fertilizers (if used) are hand-broadcast. Despite the high rainfall, the region is characterized by frequent and sometimes long dry spells during the monsoon, and low rainfall at critical nursery and transplantation stages which causes complete crop failure in rice (Cornish et al., 2010; Cornish et al., 2015). In Jharkhand, rice production is overwhelmingly carried out under rainfed conditions (>90% of the area) making it vulnerable to these fluctuations in rainfall.

In addition to an unreliable rice harvest, crop diversity in Jharkhand is very low with 84% of the food crop area under cereals and only 7% under pulses. Jharkhand produces a little less than half of its food grains requirement and as a result, *per capita* food grain availability, including pulses (13–14 gm), has been 230 gm against 523 gm for all-India and below the minimum requirement of 480 gm/day (Singh, n.d.). There is thus a dire need to increase crop diversity to reduce the reliance on a risky rice crop and improve nutritional outcomes.

Crop diversification could reduce the risks of rice production and provide cash income which is not generated from a rice monoculture. This might lead to reduced seasonal migration for off-farm work and improve diet and health outcomes of the community. A lack of cash crops, highly priced vegetables, and insufficient income to purchase diverse nutritious vegetables leads the community to collect a few leafy vegetables from waste land. These are typically dried and used with rice (Ravishankar et al., 2015), particularly in the rainy season. Crop diversification in rice-based systems, especially with vegetables (Birthal et al., 2015), has been recognized as an effective strategy for fulfilling the objectives of enhancing productivity, food security (Kleinhenz et al., 1996; Panda, 2014) and nutrition (Rajendran et al., 2017), with judicious use of resources for marginalized farmers (Singh, 2010). The upland regions are quite suitable for *kharif* (monsoon) pulses such as pigeon pea (*Cajanus cajan*), urdbean (*Vigna mungo*), mungbean (*Vigna radiata*) and horse gram (*Macrotyloma uniflorum*). Slightly lower in the landscape, the "medium land" is suitable for rabi (winter) pulses like chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), and garden pea (*Pisum sativum*). Low land is generally vacated after the harvest of transplanted rice during the 2nd week of December to the 2nd week of January when there remains some residual soil moisture (Cornish et al., 2015).

While crop diversification through the inclusion of high-value crops by broadening the base of the cropping system utilizes various techniques, such as inter-cropping/mixed cropping and other efficient management practices (Dalal and Shankar, 2022), such studies have typically been conducted without farmer involvement and may not be viable or have effective paths for adoption by communities. To improve the adoption of research outcomes, reduce food insecurity and poverty, and improve the livelihoods of women, we worked alongside tribal women farmers and helped them to explore vegetable crop options to try and diversify their own food production, increasing household nutrition and potentially cash incomes. The farmers experimented with vegetable crop options in upland and medium upland landscapes in 2014 and 2015 during the monsoon season (June to September) with support from the project team, and these were compared to the risks and opportunities of their traditional rice crops. It was thought that alternate crops to rice which require less water and can survive under variable rainfall conditions might be a highly valuable adjunct to rice in medium and upland regions.

## Materials and methods

### Geographic and cultural setting

We focused on three districts, Bokaro and West Singhbhum in the State of Jharkhand, and Purulia in the far west of West Bengal (Figure 1). While Purulia is on the EIP, much of West Bengal is not. Most of the area is covered with sandy loam to loam, acidic soils (pH 4.5–6.5) of low fertility. About 50% of soils are extremely to strongly acidic (pH <5.5). More than half of the soils in the region are low in available phosphorus (P), 18% low in potassium (K), 38% low in sulfur (S), and 45% are deficient in available boron (Petare et al., 2016). The water-holding capacity of soils in EIP are very low due to porous nature of the soil and undulating topography.

### Approach to engagement

The project team worked with one women's self-help group (SHG) comprising 25–40 women farmers at each of the three locations. The farmers were asked to highlight existing problems of farming (with rice) and for possible solutions (different methods of rice cultivation and alternatives to rice especially with vegetables). The discussion was facilitated by PRADAN (Professional Assistance for Development Action), an NGO that has been working effectively in the region for some time and staff from World Vegetable Center (WorldVeg). The primary objective was to help people in marginalized communities develop their own skills and initiatives, rather than delivering services or solutions to them. The women farmers learn through experience how to build their livelihoods and to access the information they need to engage effectively with government authorities and other people in power. The aim is for a systemic and positive change in the social, psychological and economic condition of the farmers so they can take charge of their lives and engage with the world around them. By providing a favorable environment for the discussions, options which were brought up by the farmers were critically evaluated by the group. The farmers in the group themselves decided on the options to evaluate in experiments. Many possible cropping systems were discussed in the SHG meetings, from which the following four cropping options emerged as favored by the women [trellised cucurbits, autumn (*kharif*) tomatoes, legumes in rotations and legume-maize intercropping], based on the feasibility to grow, water requirements, and local preferences including marketing.

The capacity of the farmers to conduct the research on their land was a function of their household risk profile and literacy which was discussed among the SHG. Initial support on the trial design and selecting control plots was provided by the project staff. Every month the farmers SHG met and discussed the progress and challenges and the options to mitigate these. Thus, the farmers conducted the research by themselves in a favorable environment with support from their peers and project staff. These experiments were conducted for 2 years (2013–2014 and 2014–2015), and each year the crops and the experiments to be conducted were decided by the farmers group, based on the previous season learnings. Project field staff trained capable farmers to record data such as the input costs, dates of cultural operations, hours of labor, harvesting, marketable and unmarketable yields, home consumption and price of the harvested products. Initially the project staff helped in recording and maintaining the data but the farmers then took on the data acquisition with supervision from project staff. The SHG women farmers were present during the data recording and all data were validated by the field staff.

The average household land availability for farming is less than 0.5 ha and spread across the upland, middle land and low land. Because it is quite wet, low land can be used only for paddy cultivation, thus upland and middle land were used for conducting trials ranging from 150 to 500 $m^2$ (details in Table 1). The practices of the trials were approximately uniform but the experimental area depended on the farmer resources (land see Table 1) and labor. A

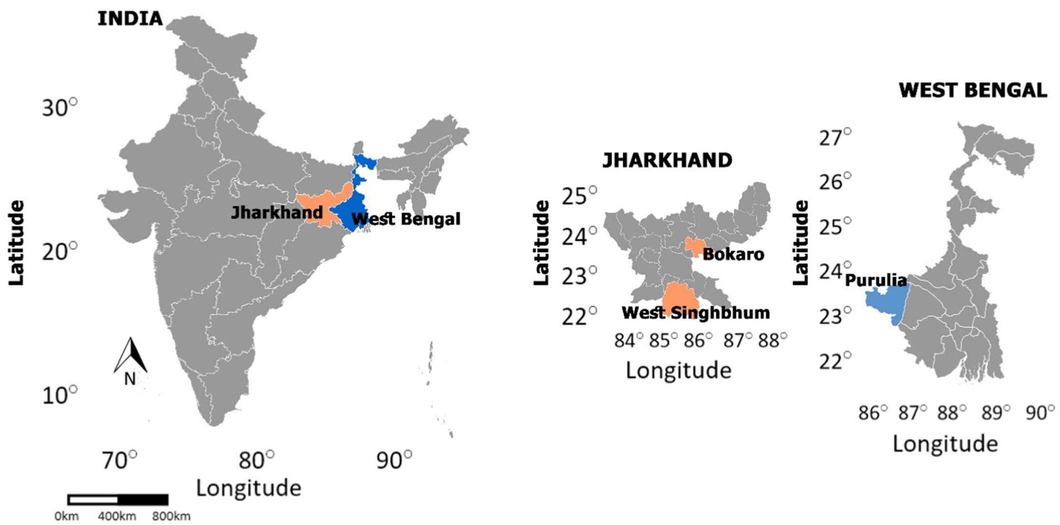


FIGURE 1
Location of study sites in India.

TABLE 1 Crop diversity of vegetables and cropping area from 2013 to 2015 during autumn (*kharif*) and winter (*rabi*) season across three research villages and farmers.

| Sl.no. | Crop | Village | Season | Number of farmers (Year wise) | | | Cropping area (ha) of vegetables | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 2013 | 2014 | 2015 | 2013 | 2014 | 2015 |
| 1 | Trellis | | | | | | | | |
| 1.1 | Cucumber | Bhubhui | *kharif* | 4 | 1 | 1 | 0.1 | 0.023 | 0.024 |
| 1.2 | Pointed gourd | | *kharif* | 1 | 2 | 4 | 0.023 | 0.054 | 0.12 |
| 1.3 | Sponge gourd | | *kharif* | 0 | 4 | 0 | 0 | 0.039 | 0 |
| 1.4 | Bottle gourd | | *kharif* | 0 | 0 | 2 | 0 | 0 | 0.054 |
| 2 | DSR + Black gram | | *kharif* | 5 | 0 | 0 | 1.67 | 0 | 0 |
| 3 | Tomato | | *kharif* | 7 | 4 | 4 | 0.29 | 0.14 | 0.14 |
| 4 | Sweet potato + pigeon pea | | *kharif* | 5 | 5 | 0 | 0.46 | 0.46 | 0 |
| 5 | Chick pea | | *rabi* | 0 | 4 | 0 | 0 | 0.18 | 0 |
| 6 | Garden pea | | *rabi* | 0 | 2 | 0 | 0 | 0.06 | 0 |
| | Total | | | 22 | 22 | 11 | 2.543 | 0.956 | 0.338 |
| | | Talaburu | | | | | | | |
| 1.1 | Cucumber | | *kharif* | 3 | 5 | 3 | 0.37 | 0.034 | 0.077 |
| 1.2 | Bitter gourd | | *kharif* | 6 | 1 | 2 | 0.42 | 0.029 | 0.053 |
| 1.3 | Bottle gourd | | *kharif* | 1 | 0 | 0 | 0.32 | 0 | 0 |
| 2 | Mungbean | | *kharif* | 2 | 7 | 0 | 0.06 | 0.32 | 0 |
| 3 | Tomato | | *kharif* | 0 | 5 | 5 | 0 | 0.2 | 0.25 |
| 4 | Chickpea | | *rabi* | 9 | 5 | 2 | 0.26 | 0.13 | 0.03 |
| 5 | Tomato | | *rabi* | 6 | 0 | 0 | 0.25 | 0 | 0 |
| 6 | French bean | | *rabi* | 4 | 0 | 0 | 0.3 | 0 | 0 |
| 7 | Garden pea | | *rabi* | 4 | 0 | 0 | 0.11 | 0 | 0 |
| | Total | | | 35 | 23 | 12 | 2.09 | 0.713 | 0.41 |
| | | Churinsara | | | | | | | |
| 1.1 | Cucumber | | *kharif* | 3 | 0 | 0 | 0.067 | 0 | 0 |
| 1.2 | Bitter gourd | | *kharif* | 3 | 0 | 0 | 0.057 | 0 | 0 |
| 2 | Maize+legume | | *kharif* | | | | | | |
| 2.1 | Maize+cowpea | | *kharif* | 2 | 0 | 0 | 0.045 | 0 | 0 |
| 2.2 | Maize+ veg soybean | | *kharif* | 4 | 0 | 0 | 0.122 | 0 | 0 |
| | Maize+French bean | | *kharif* | 3 | 12 | 12 | 0.1 | 0.48 | 0.48 |
| 3 | Tomato | | *kharif* | 10 | 11 | 11 | 0.52 | 0.52 | 0.52 |
| 4 | Mungbean | | *kharif* | 3 | 0 | 0 | 0.007 | 0 | 0 |
| | Chickpea | | *rabi* | 6 | 0 | 0 | 0.25 | 0 | 0 |
| | French bean | | *rabi* | 3 | 0 | 0 | 0.04 | 0 | 0 |
| | Garden pea | | *rabi* | 5 | 0 | 0 | 0.09 | 0 | 0 |
| | Total | | | 42 | 23 | 23 | 0.778 | 1 | 1 |
| | Grand Total | | | 99 | 68 | 46 | 5.41 | 2.66 | 1.74 |

village level research management committee was formed where the research famers, data collectors and SHG leadership were members. They meet every week for planning and review of progress. Apart from these meetings, frequent field visits were organized to observe and reflect upon the research activity. The research plots were treated as a learning resource for the whole community, farmers made observations and shared what the results meant to them. Any difficulty in implementation was shared in the weekly meetings and all required support was provided by the SHG. At the end of each crop season a reflection meeting was organized, where almost the whole village and the scientist alongwith PRADAN team were present to share the observations and reflect on what are the learnings were and how it will influence the next season plans.

## Field experiments

Tables 1, 2 outline the four different crop diversification strategies explored, (i) cucurbits *kharif* season, June to September, (ii) growing tomatoes in the "off season" (monsoon), July to October, (iii) growing legume crops in rotation with direct sown rice (*rabi* season), November to January, and (iv) intercropping beans with maize (autumn/*kharif*/rainy season-June to September). In total 213 experiments were established by the farmers (Table 1).

The cucurbits and tomatoes were grown in traditionally rice grown fields as treatments along with the traditional rice for comparison. The intercropping of beans with maize was introduced in the sole maize grown land with sole maize as control plots. To utilize the soil residual moisture after the direct sown rice crop (due to early harvest of direct sown rice), legumes such as garden pea, French bean (*Phaseolus vulgaris*) and chickpea were introduced, otherwise the lands are not utilized for crops. The full details of the vegetable culture experimental methods are provided as Supplementary material, these are subservient to the experiments being used as a vehicle for farmer learning, empowerment and sharing of learnings among the women farmers.

An economic assessment of the production systems deployed was undertaken. The cost of cultivation was calculated by adding all input costs (field preparation, input supplies, trellising, irrigation, labor days at local prevailing cost etc.), and the net profit was calculated by deducting the total sales (including the family consumption) from the total cost incurred in the cultivation practice. The quantity of vegetables consumed in-house from the harvest also was recorded. We also assessed the economics of the typical practice of crop cultivation (mostly broadcasted paddy) as a nominal comparative control.

# Economic analysis

A simple economic analysis was conducted for each of the enterprises. Labor (man days @ 8 h per day) was costed at the local village INR/day rate, including the family and the hired labor. The labor cost thus varied by village at the prevailing rate at the time of experiment. Trellising for vegetable production was costed at 3,000 INR for one tenth of an acre (0.04 ha). The trellis was assumed effective for 3 years for two crops per year for cucurbits, except for pointed gourd which is perennial, where one crop was harvested per year. The trellis cost was thus amortized across three subsequent years. The prices received for produce by each individual farmer was used to calculate income for each plot. Although rice is primarily used for home consumption, we have placed a value of 6.6 INR/kg (based on the production cost) for it so that it can rationally be compared with income from vegetable production or the opportunity cost for land and labor. Household consumption of vegetables and rice produced was included in the net income calculated.

Net Income (INR per plot) = Income (INR per plot) – Cost (INR per plot), includes the value of home consumption.

Income (INR per plot) = Sum of [marketable yield each harvest multiplied by selling rate (INR per kg)].

Cost (INR per plot) = All input costs (cost of seed+ fertilizer cost + pesticides cost + cost of agronomic practices+ cost of labor including family labor used for all the activities). The land rental value, depreciation cost, and interest on operating cost were not included as the primary aim is to analyze the incremental income from crop diversification with the similar land was used as control plot.

## Statistical analysis

To test the significance of the rankings for each treatment, Kruskall-wallis non-parametric test (SAS v9.4, SAS Institute Inc., 2018) was performed for one- and two-way classified data, respectively, by using chi-square statistics. Multiple comparisons were done for significant factors.

# Results

## Cucurbits

The cultivation of cucurbit crops on trellises in the medium uplands provided a nominal eightfold increase in net income as compared to the traditional cultivation of paddy rice (Table 3). The cucurbit crop also contributed to diet diversification, as farmers consumed these vegetables at an average of 24 kg per family (Table 3, calculated based on the actual data on the vegetables consumed). Old trellises were used with minimum needed repairs. Pointed gourd was a new crop cultivated in this area and it provided the highest income from the unit area (0.04 ha) when compared to other vegetables (Table 4).

In the medium uplands (Table 5) the trellised cucurbits provided an almost sixfold increase in net income compared to the value of broadcasted paddy (traditional practice). It was observed that the bitter gourd crop had more fruit fly infestations than cucumber.

TABLE 2 Number of experimental units established in each location in each year.

| System | Bokaro | | Purulia | | West Singhbhum | |
|---|---|---|---|---|---|---|
| | 2014 (9) | 2015 (15) | 2014 (22) | 2015 (17) | 2014 (14) | 2015 (14) |
| Trellised cucurbits | 7 | 4 | 0 | 0 | 6 | 4 |
| Autumn/ *kharif*/tomatoes | 2 | 4 | 9 | 10 | 0 | 3 |
| Legume rotations | 0 | 7 | 4 | 0 | 8 | 7 |
| Legume-maize intercrops | 0 | 0 | 9 | 7 | 0 | 0 |

Figures in parenthesis is the total number of trials.

Non-parametric tests showed that mean scores for cultivation of bitter gourd and cucumber on trellis have a greater net income ($p > 0.11$) compared to broadcasted paddy (Table 5B).

Even though cucurbit cultivation on trellises required 51% more labor and incurred 63% more labor costs than traditional paddy farming, the net income per ha was 93% higher from cucurbits compared to traditional paddy. The income per ha as well as net income obtained from the cultivation of cucurbits was significantly greater ($p < 0.05$) than from traditional paddy (Table 5A). Cucurbits also provided additional household nutrition as farmers consumed these vegetables on an average 63 kg per family over a 2–3-month period. Among cucurbits, pointed gourd was found to be the most profitable crop as it provided 86% more net income per ha than bottle gourd and cucumber. Owing to the perennial nature of pointed gourd, some farmers also obtained income from the same crop during the second or third year from the same crop.

Cultivation of cucurbit crops on trellis in medium upland provided 76% increase in net income in West Singhbhum village (Table 5A). Among cucurbits, cucumber provided 48% more net income than bitter gourd (Table 6).

## Out of season tomatoes

For *kharif* grown tomatoes in Churinsara in 2014 the yield of the most common variety (15.3 t/ha, Lakshmi-5005) was significantly different ($p > 0.0009$) from only one other variety, GS-600, which yielded very poorly due to its long duration and pest and disease infestations. Although some of the other varieties yielded slightly higher, the differences were not statistically significant (Figure 2). Nevertheless, differences in yield and variety translated into significant differences for net income ($p > 0.0003$) with varieties Swarma Anmol and Rohit-2 providing significantly greater income than the two lowest yielding varieties (GS-600 and Himraj, Table 6A).

Four varieties, namely JKTH-882 (JK Seeds), Rohit-2 (Seminis), Swarna Anmol (ICAR) and Lakshmi-5005 (Nunhems), were evaluated for yields during the 2014 rainy season at Gola district (Table 6B). Swarna Anmol had the highest average yield (14.4 t/ha) and net income (307,571 INR/ha) followed by Rohit-2 which recorded a yield of 12.9 t/ha and an average net income of 265,981 INR/ha in two farmers' fields. The yield increases of Swarna Anmol and Rohit-2 over the control Lakshmi-5005 was 63 and 46%, respectively, with an

TABLE 3 Economics of trellis vegetable, traditional paddy and maize cultivation for 2014 and 2015 of Bhubhui, Talaburu, and Churinsaru villages.

| | Bhubhui | | | Talaburu | | | Churinsara[b] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trellis | Tomato | Paddy | Trellis | Tomato[a] | Paddy | Tomato | Maize+legume | Maize |
| 2014 | | | | | | | | | |
| Plot area (m$^2$) | 150 | 100 | 200 | 310 | 0 | 680 | 430 | 400 | 200 |
| Economic yield (t/ha) | 1.6 | 14.4 | 2.2 | 4.7 | 0 | 1.7 | 20.6 | 15.7 | 14.4 |
| Net income (INR/plot) | 2,858 | 2,245 | 43 | 3,745 | 0 | 1,739 | 7,614 | 3,763 | 1,078 |
| Labor days/plot | 11.1 | 4.9 | 1.6 | 6.7 | 0 | 13.1 | 13.8 | 15.9 | 5.6 |
| Return on labor (INR/day) | 257 | 458 | 27 | 559 | 0 | 133 | 552 | 237 | 192 |
| 2015 | | | | | | | | | |
| Plot area (m$^2$) | 260 | 170 | 270 | 300 | 310 | 900 | 470 | 350 | 200 |
| Economic yield (t/ha) | 5.5 | 15.5 | 5.4 | 5.9 | 7.0 | 1.7 | 13.0 | 4.1 | 2.3 |
| Net income (INR/plot) | 12,120 | 3,379 | 870 | 2,392 | 4,376 | 1,696 | 4,530 | 1,834 | 224 |
| Labor days/plot | 20.5 | 8.3 | 10.4 | 8.5 | 7.2 | 16.4 | 12.8 | 5.8 | 3.4 |
| Return on labor (INR/day) | 591 | 407 | 84 | 281 | 608 | 103 | 354 | 316 | 66 |

[a] No tomato yield data due to seedling damage by heavy rains. [b] Insufficient rain in Churinsara to transplant paddy rice.
Net Income (INR per plot) = Income (INR per plot) – Cost (INR per plot), excludes the value of home consumption.
Income (INR per plot) = Sum of [marketable yield each harvest multiplied by selling rate (INR per kg)].
Cost (INR per plot) = All input costs (cost of seed + fertilizer cost + pesticides cost + cost of agronomic practices + cost of labor used for all the activities).

TABLE 4 Vegetable consumption (kg/Household) before and after project intervention during autumn (*kharif)* season.

| Location | Vegetable consumption before project intervention (kg) | | Vegetable consumption after the project intervention (kg) | | | |
|---|---|---|---|---|---|---|
| | | | 2014 | | 2015 | |
| | Tomato | Cucurbits | Tomato | Cucurbits | Tomato | Cucurbits |
| Bhubhui | 2.5 (8) | 13 (7) | 6 (8) | 24(7) | 16 (3) | 63 (5) |
| Talaburu | Nil (3) | 4 (5) | 6 (2) | 9 (HH) | 49 (3) | 12 (4) |
| | Tomato | French bean | Tomato | French bean | Tomato | French bean |
| Churinsara | Nil (11) | Nil (9) | 17 (11) | 3 (9) | 37 (10) | 7 (5) |

Figures in the parentheses followed by the data are the corresponding household.

increase in net income of 101 and 74%, respectively. However, there was no significant difference between the varieties ($p < 0.21$) for yield (Table 6C). Besides improving their incomes, farmers also consumed tomatoes on an average of 1.5–6.5 kg per family.

Based on the results of varietal evaluation trials during the 2014 rainy season in Churinsara village of Purulia district of West Bengal (highest yield 20.63 t/ha and income were recorded from Rohit-2), farmers selected this variety for cultivation during *kharif* 2015. They obtained an average yield of 13 t/ha ranging from 8 and 30 t/ha and an average net income of 96,378 INR/ha (Table 6D) and in Talaburu, during the *kharif* season in 2015, the yield ranges from 5.7 to 10.6 t/ha with the mean yield of 7 t/ha and mean net income of 1,41,152 INR/ha (Table 6E).

## Introduction of legume crops in rotation with paddy

Out of the three French bean varieties, Falguni (Seminis Seeds) yielded highest (6.5 t/ha) which is on par with the variety Falguna (Jagdish Seeds) (Table 7). While the average net income/ha obtained from Falguna is 41% higher than from Falguni, primarily due to a higher market preference due to its soft and fleshy pods, the non-parametric tests indicated that the differences between the varieties were not significantly different for net income ($p > 0.47$) (Table 7A).

In the case of garden pea (Table 8), KSP – 110 (Kalash Seeds Pvt., Ltd.) had the highest average yield of 7.32 t/ha and average net income of 112,424 INR/ha but, the non-parametric tests showed that there were no significant differences between the varieties for yield ($p > 0.50$) or net income ($p > 0.67$, Table 8A).

## Intercropping legumes with maize

The farmers earned an average net income of 94,079 INR/ha by growing a legume intercropped with maize, 74% more than that of the average net income of seven comparable farmers growing maize as a sole crop (Table 9). Among the legume crops, French bean yields (0.72 t/ha) were greater than those of yard long bean (0.19 t/ha). The yield of the maize under intercropping also increased when compared to sole maize without intercropping due to better

TABLE 5 Yield and income generated by cucurbits on trellis against traditional paddy in medium upland in Bhubhui village during autumn (*kharif*) 2015.

| Farmer | Crop | Plot size (ha) | Yield (kg/plot) | Cost (INR 1,000/ha) | Income (INR 1,000/ha) | Net income (INR 1,000/ha) | Home consumption (kg/plot) | Labor day/ha | Total labor cost (INR 1,000/ha) |
|---|---|---|---|---|---|---|---|---|---|
| Farmer A | Bottle gourd | 0.023 | 189 | 82.4 | 142.5 | 60.1 | 25 | 529 | 52.9 |
| Farmer B | Pointed gourd | 0.029 | 1,639 | 189.6 | 1350.0 | 1160.4 | 107 | 1,230 | 123.0 |
| Farmer C | Pointed gourd | 0.026 | 919 | 174.5 | 935.4 | 760.9 | 60 | 1,203 | 120.3 |
| Farmer D | Cucumber | 0.024 | 306 | 95.0 | 233.9 | 138.8 | 40 | 531 | 53.1 |
| Farmer E | Bottle gourd | 0.031 | 795 | 77.3 | 287.8 | 210.5 | 85 | 441 | 44.1 |
| Farmer F | Traditional paddy | 0.041 | 186 | 37.7 | 72.1 | 34.4 | 186 | 249 | 19.9 |
| Farmer G | Traditional paddy | 0.030 | 118 | 40.9 | 66.6 | 25.7 | 118 | 303 | 23.9 |
| Farmer H | Traditional paddy | 0.030 | 226 | 50.6 | 120.4 | 69.8 | 226 | 347 | 27.8 |
| Farmer I | Traditional paddy | 0.016 | 64 | 69.5 | 63.0 | −6.5 | 64 | 549 | 44.7 |
| Farmer J | Traditional paddy | 0.021 | 146 | 64.7 | 112.6 | 48.0 | 146 | 472 | 37.9 |
|  | Mean | 0.027 | 148 | 52.7 | 86.9 | 34.3 |  | 384 | 28.7 |

Price (INR): Bottle gourd 6–18/kg; pointed gourd 20–25/kg; cucumber 17–30/kg; paddy grains = 15/kg; paddy straw = 1/kg.

TABLE 5A Wilcoxon rank sum scores for income/ha and Net income/ha for cucurbits (all vegetables) on trellis against traditional paddy in medium upland in Bhubhui and West Singhbhum and village during autumn (*kharif*) 2015.

| Village | Variable | TRT | Sum of scores | Mean score | Chi-square | Prob>Chisq |
|---|---|---|---|---|---|---|
| Bhubhui | Income/ha | Vegetable | 40 | 8.00 | 6.82 | 0.009 |
|  | Income/ha | Paddy | 15 | 3.00 |  |  |
|  | Net income/ha | Vegetable | 39 | 7.80 | 5.77 | 0.016 |
|  | Net income/ha | Paddy | 16 | 3.20 |  |  |
| West Singhbum | Income/ha | Vegetable | 26 | 6.50 | 5.33 | 0.021 |
|  | Income/ha | Paddy | 10 | 2.50 |  |  |
|  | Net income/ha | Vegetable | 25 | 6.25 | 4.08 | 0.043 |
|  | Net income/ha | Paddy | 11 | 2.75 |  |  |

agronomic practices such as line sowing and associated weeding, and generally improved crop management in the intercrops (Table 9A).

In Purulia, West Bengal the intercropping of vegetable French bean (local variety) with maize varieties Kanchan 25 and Kaveri, were evaluated by seven farmers during the 2015 rainy season (Table 9B). Based on the experience of the previous year farmers selected French bean as the preferred intercrop. The farmers earned an average net income of 52,400 INR/ha which is 78% more than that of the average net income of the farmers (three) growing maize as a sole crop. Average yield of French bean was 0.59 t/ha as an intercrop. The yield of the maize under intercropping again increased by 44% when compared to sole maize. Labor use per hectare of land and labor cost per hectare were nearly same for both the cases but net income per ha were very different ($p < 0.05$). Income per ha INR 91,900 vs. INR 46,100 ($p = 0.017$) as well as net income, INR 52,400 vs. 11,200 ($p = 0.017$) obtained from the intercropping was significantly greater than from sole maize crop (Table 9C).

**TABLE 5B** Wilcoxon rank sum of scores (Kruskal-Wallis test) for Net income/ha for vegetables (bitter gourd and cucumber) on trellis against broadcasted paddy in the medium uplands.

| | Wilcoxon scores (rank sums) | | | | |
|---|---|---|---|---|---|
| Variable | TRT | Sum of scores | Mean score | Chi-square | Prob > Chisq |
| Net income/ha | Bitter | 11 | 5.5 | 4.46 | 0.11 |
| Net income/ha | Cucumber | 14 | 7 | | |
| Net income/ha | Paddy | 11 | 2.75 | | |

## Discussion

Growing rainy season vegetables (cucurbits in trellis, tomatoes, legume maize intercropping and legumes in rotation with the paddy) in these three locations proved to be a promising and economic alternative. Growing cucurbits under a trellis system, especially cucumber, proved to be the better option. Although the initial investment is high in the case of cultivation of pointed gourd due to the cost of planting materials such as rhizomes or cuttings, and horizontal trellising is necessary, which adds to the production costs, the cost reduces in subsequent years due to the perennial nature of the crop which needs only maintenance in subsequent years. This crop also helps in promoting local entrepreneurship through raising the seedlings of pointed gourd locally and also helps other farmers to easily access pointed gourd seedlings. The farmers of Bhubhui village were interested in expanding the area of pointed gourd crops and began to produce seedlings from cuttings of pointed gourd in their village and sold these seedlings to neighboring villages at 10 INR/seedling. This was a somewhat unexpected outcome but illustrates the courage and empowerment of the farmers.

**TABLE 6** Yield and income generated by tomato cultivation in upland in Churinsara during 2014.

| Replication | Yield (t/ha) performance of tomato varieties | | | | | |
|---|---|---|---|---|---|---|
| | GS-600 | JKTH-882 | Himraj | Swarna Anmol | Rohit-2 | Lakshmi-5005 |
| Farmer A | 4.51 | 18.46 | 8.40 | 25.75 | 24.17 | 7.21 |
| Farmer B | 1.31 | 11.52 | 10.79 | 27.83 | 20.94 | 19.98 |
| Farmer C | 1.07 | 15.76 | 13.57 | 25.35 | 23.02 | 14.71 |
| Farmer D | 1.55 | 14.44 | 5.07 | 10.98 | 10.12 | 3.63 |
| Farmer E | 7.24 | 31.05 | 23.58 | 29.82 | 26.62 | 29.11 |
| Farmer F | 3.16 | 10.44 | 11.19 | 18.13 | 19.31 | 24.70 |
| Farmer G | 15.63 | 14.47 | 10.73 | 19.18 | 26.15 | 20.12 |
| Farmer H | 2.19 | 5.01 | 3.32 | 6.71 | 10.81 | 2.65 |
| Farmer I | 6.94 | 13.12 | 12.97 | 12.88 | 24.51 | 15.53 |
| Mean | 4.84 | 14.92 | 11.07 | 19.62 | 20.63 | 15.29 |
| | Net income (INR 1,000/ha) obtained from different varieties | | | | | |
| Farmer A | 47.7 | 311.8 | 142.2 | 465.9 | 386.2 | 110.5 |
| Farmer B | −9.3 | 165.5 | 149.0 | 490.6 | 323.0 | 347.0 |
| Farmer C | −7.8 | 188.1 | 175.0 | 377.2 | 318.9 | 221.2 |
| Farmer D | −0.6 | 205.9 | 63.6 | 183.2 | 142.8 | 198.3 |
| Farmer E | 37.4 | 332.8 | 271.4 | 347.9 | 296.8 | 319.6 |
| Farmer F | 24.9 | 88.9 | 98.9 | 170.4 | 208.2 | 246.7 |
| Farmer G | 151.5 | 137.0 | 97.6 | 225.6 | 300.6 | 207.4 |
| Farmer H | 0.3 | 27.5 | 11.5 | 43.9 | 85.6 | 3.5 |
| Farmer I | 55.3 | 124.2 | 108.3 | 122.4 | 268.7 | 150.4 |
| Mean | 33.3 | 175.7 | 124.2 | 269.7 | 259.0 | 200.5 |

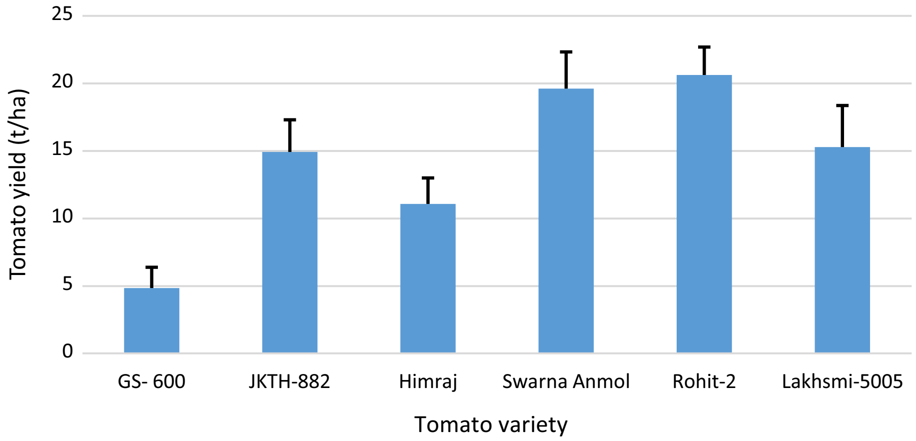


FIGURE 2
Yield of tomato varieties grown in the off (autumn/*kharif* season) season in Churinsara 2014 (error bars are the standard error of the mean for $n=9$).

**TABLE 6A** Wilcoxon (Kruskal-Wallis test) scores for yield t/ha and Net income/ha for tomato cultivation in upland in Churinsara during 2014.

| Yield (t/ha) | | | | | Net income/ha | | | |
|---|---|---|---|---|---|---|---|---|
| TRT | Sum of scores | Mean score | Chisq | Prob>Chisq | Sum of scores | Mean score | Chisq | Prob>Chisq |
| GS-600 | 86 | 9.56 | 20.81 | 0.0009 | 76 | 8.44 | 23.13 | 0.0003 |
| JKTH-882 | 262 | 29.11 | | | 252 | 28.00 | | |
| Himraj | 193 | 21.44 | | | 189 | 21.00 | | |
| Swarna | 330 | 36.67 | | | 336 | 37.33 | | |
| Rohit-2 | 347 | 38.56 | | | 343 | 38.11 | | |
| Lakhsmi | 267 | 29.67 | | | 289 | 32.11 | | |

**TABLE 6B** Yield and income generated by tomato cultivation in medium upland in Bhubhui during 2014.

| Variety | Yield(t/ha) | | Mean yield (t/ha) | Net income (INR 1,000/ha) | Percent yields increase over control | Percent net income increase over control | Home consumption (kg/plot) | | |
|---|---|---|---|---|---|---|---|---|---|
| | R1 | R2 | – | – | – | – | R1 | R2 | Mean |
| JKTH-882 | 11.55 | 7.86 | 9.71 | 171.3 | 10.22 | 11.8 | 2.5 | 1.5 | 2.0 |
| Rohit-2 | 15.05 | 10.76 | 12.9 | 307.6 | 46.42 | 100.76 | 12 | 6.0 | 9.0 |
| Swarna Anmol | 13.10 | 17.51 | 14.4 | 266.0 | 63.45 | 73.62 | 1.5 | 1.5 | 1.5 |
| Control (Lakshmi-5005) | 8.29 | 9.32 | 8.81 | 153.2 | – | – | 7.0 | 6.0 | 6.5 |

In the *kharif* season farmers of Churinsara village faced problems of water scarcity and little rains, and the rice crop failed. In this situation, income from tomato contributed significantly to their livelihood. Thus, diversifying into vegetables reduces risk and the catastrophe that comes from over reliance on subsistence rice (Cornish et al., 2015). In addition to cash income, farmers also consumed tomatoes on an average 37 kg per family, improving economic security, nutrition and health. Similarly, growing legumes, especially French bean as an intercrop with maize, helped the farmers with early income during the lean rainy season and helps them in continuing their livelihood to purchase inputs for other crops, especially paddy which will remain the major crop. Apart from that French bean added nutrition to the meal of the poor community as well created social harmony through its distribution among neighbors and relatives. The availability and affordability of vegetables during the rainy season is usually very limited for the tribal people of the study area and while no formal survey on household consumption of vegetables which farmers grew during the rainy season was conducted, at the commencement of the project, all of the farmers who were going to participate in the vegetable growing experiments were asked about the availability of vegetables for home consumption before the project intervention, specifically during the rainy season (*kharif*). Discussions with farmers and field staff revealed that vegetable availability increased significantly during the project intervention, either through their own production or by giving vegetables to neighbors without the need for purchase. This increase in availability corresponded with an increase in home consumption of vegetables. Although there have been a number of studies exploring crop diversity and diet diversity of smallholders in India (e.g., Chinnadurai et al., 2016; Anuja et al., 2020, 2022), these have essentially been meta-analysis of regional statistical data rather than the first hand observations evident in the present study.

Rotation of legumes with direct sown rice gives some additional income to the farmers, but the availability of the residual soil moisture is an issue as the soil water is rapidly exhausted. French bean and garden pea demanded more water compared to chickpea and thus legumes following rice might be more beneficial for farmers with some contingency irrigation (Mukherjee, 2015). Working directly alongside farmers, we have shown that vegetable production can provide an important and viable adjunct to paddy rice production, securing cash income and the ability to buy food when the rice crop fails, improving household diet diversity and nutrition and income to also purchase inputs for rice production or other essential family items such as health services. Many studies also reported increased income and profit by substituting vegetables in the paddy lands (Kleinhenz et al., 1996; Singh et al., 2022). A key element of this work has been the engagement of famers in the research activity which gives them the ability to continue to experiment and develop new systems within their own communities.

For the smallholder farmers of this region growing vegetables is comparatively difficult compared to the paddy, due to lack of knowledge of agronomic practices, more inputs required and risk of pest and diseases. These are perceived as main impediments during the process of introduction. Although more labor per unit land is required for vegetable production it has been found to be highly profitable, especially for families with smaller holdings and thus a higher labor:land ratio (Joshi et al., 2006; Birthal et al., 2015). In future, the occurrence of pests and diseases may increase due to area expansion and continuous cultivation of the vegetables. Since the farmers or the citizens have been involved in all the

TABLE 6C Wilcoxon (Kruskal-Wallis test) scores for yield t/ha for tomato cultivation in medium upland in Bhubhui during 2014.

| Yield (t/ha) | | | | |
|---|---|---|---|---|
| TRT | Sum of score | Mean score | Chisq | Prob>Chisq |
| JKTH-882 | 6 | 3.00 | 4.50 | 0.2123 |
| Rohit-2 | 11 | 5.50 | | |
| Swarna-Anmol | 14 | 7.00 | | |
| Lakshmi-5005 | 5 | 2.50 | | |

TABLE 6D Yield and income generated by tomato cultivation in upland in Churinsara during autumn (*kharif)* 2015.

| Farmer | Area (ha) | Yield (kg/ plot) | Yield (t/ha) | Cost of cultivation (INR 1,000/ha) | Income (INR 1,000/ha) | Net income (INR 1,000/ha) | Home consumption (kg/family) | Labor day/ ha | Total labor cost (INR 1,000/ha) |
|---|---|---|---|---|---|---|---|---|---|
| Farmer A | 0.050 | 583 | 12 | 70.8 | 156.2 | 85.4 | 49 | 270 | 1.4 |
| Farmer B | 0.050 | 459 | 9 | 69.3 | 128.1 | 58.7 | 36 | 255 | 1.3 |
| Farmer C | 0.044 | 540 | 12 | 76.6 | 167.3 | 90.7 | 39 | 289 | 1.3 |
| Farmer D | 0.045 | 445 | 10 | 75.1 | 155.0 | 79.9 | 22 | 281 | 1.3 |
| Farmer E | 0.044 | 548 | 13 | 75.6 | 112.7 | 37.1 | 35 | 277 | 1.2 |
| Farmer F | 0.050 | 581 | 12 | 70.3 | 151.8 | 81.5 | 26 | 263 | 1.3 |
| Farmer G | 0.048 | 1,430 | 30 | 76.5 | 415.4 | 338.9 | 38 | 314 | 1.5 |
| Farmer H | 0.050 | 390 | 8 | 68.3 | 98.8 | 30.5 | 36 | 243 | 1.2 |
| Farmer I | 0.042 | 446 | 11 | 80.2 | 164.3 | 84.1 | 42 | 250 | 1.3 |
| Farmer J | 0.053 | 667 | 13 | 67.8 | 144.7 | 76.9 | 45 | 275 | 1.3 |
| Mean | 0.048 | 609 | 13 | 73.1 | 169.4 | 96.4 | 37 | 272 | 1.3 |

Price (INR): 8–30/kg.

TABLE 6E Yield and income generated by tomato cultivation in medium upland in Talaburu during 2015.

| Farmer | Area (ha) | Plot Yield (kg) | Yield (t/ha) | Cost of cultivation (INR 1,000/ ha) | Income (INR 1,000/ plot) | Income (INR 1,000/ ha) | Net income (INR 1,000/ ha) | Home consumption (kg/family) | Labor day/ha | Labor cost (INR 1,000/ ha) |
|---|---|---|---|---|---|---|---|---|---|---|
| Farmer A | 0.018 | 108 | 5.9 | 37.0 | 2.7 | 147.1 | 110.0 | 55 | 285 | 22.8 |
| Farmer B | 0.020 | 207 | 10.6 | 51.8 | 5.2 | 264.0 | 212.2 | 35 | 260 | 20.8 |
| Farmer C | 0.056 | 322 | 5.7 | 41.9 | 8.1 | 143.1 | 101.2 | 57 | 148 | 11.9 |
| Mean | 0.03 | 212 | 7 | 43.6 | 5.3 | 184.7 | 141.2 | 49 | 231 | 15.9 |

TABLE 7 Yield and income generated by French bean varieties in the medium lowlands in Talaburu during winter (*rabi)* season 2013–2014.

| Replication | Variety | Area (ha) | Yield (t/ha) | Cost (INR 1,000/ha) | Income (INR 1,000/ha) | Net Income (INR 1,000/ha) |
|---|---|---|---|---|---|---|
| Farmer A | Falguna | 0.010 | 2.48 | 43.2 | 69.9 | 26.7 |
| Farmer B | Falguna | 0.006 | 3.70 | 43.8 | 100.9 | 57.1 |
| Farmer C | Falguna | 0.005 | 6.31 | 79.6 | 151.7 | 72.1 |
| Farmer D | Falguna | 0.005 | 13.33 | 67.8 | 109.0 | 41.2 |
| Mean | | | 6.45 | 58.6 | 107.9 | 49.3 |
| Farmer E | Falguni | 0.010 | 2.06 | 43.8 | 58.2 | 14.4 |
| Farmer F | Falguni | 0.006 | 4.90 | 36.7 | 76.3 | 39.6 |
| Farmer G | Falguni | 0.005 | 6.42 | 88.7 | 154.9 | 66.2 |
| Farmer H | Falguni | 0.005 | 12.64 | 76.7 | 95.4 | 18.7 |
| Mean | | | 6.50 | 61.4 | 96.2 | 34.7 |
| Farmer I | HAFB 2 | 0.010 | 2.18 | 43.5 | 61.5 | 18.0 |
| Farmer J | HAFB 2 | 0.006 | 3.94 | 36.2 | 81.2 | 45.0 |
| Farmer K | HAFB 2 | 0.005 | 6.55 | 79.2 | 149.1 | 69.9 |
| farmer L | HAFB 2 | 0.005 | 12.14 | 66.8 | 119.7 | 52.8 |
| Mean | | | 6.20 | 56.4 | 102.9 | 46.4 |

TABLE 7A Wilcoxon (Kruskal-Wallis test) scores for Net income/ha for French bean varieties in the medium lowlands in Talaburu during winter (*rabi)* season 2013–2014.

| Net income/ha | | | | |
|---|---|---|---|---|
| TRT | Sum of scores | Mean score | Chisq | Prob > Chisq |
| Falguna | 31 | 7.75 | 1.50 | 0.4724 |
| Falguni | 19 | 4.75 | | |
| HAFB2 | 28 | 7 | | |

TABLE 8 Yield and income generated by garden pea varieties in the medium lowlands in Talaburu.

| Replication | Variety | Area (ha) | Yield (t/ha) | Yield (kg/plot) | Cost (INR 1,000/ha) | Income (INR 1,000/ha) | Net (INR 1,000/ha) |
|---|---|---|---|---|---|---|---|
| Farmer A | GS-10 | 0.0081 | 6.07 | 49.27 | 27.7 | 179.9 | 152.3 |
| Farmer B | GS-10 | 0.0087 | 7.61 | 66.05 | 33.6 | 74.4 | 40.8 |
| Farmer C | GS-10 | 0.0068 | 2.58 | 17.53 | 33.3 | 37.7 | 4.4 |
| Farmer D | GS-10 | 0.0147 | 4.07 | 59.86 | 31.3 | 80.8 | 49.5 |
| Mean | | | 5.08 | 48.18 | 31.5 | 93.2 | 61.8 |
| Farmer E | KSP-110 | 0.0081 | 8.29 | 67.27 | 23.6 | 245.7 | 222.0 |
| Farmer F | KSP-110 | 0.0087 | 5.43 | 47.11 | 30.5 | 53.1 | 22.5 |
| Farmer G | KSP-110 | 0.0068 | 9.63 | 65.49 | 48.3 | 141.0 | 92.7 |
| Farmer H | KSP-110 | 0.0147 | 5.92 | 87.11 | 28.7 | 117.6 | 112.4 |
| Mean | | | 7.32 | 66.74 | 32.8 | 139.3 | 112.4 |
| Farmer I | Komal peas-10 | 0.0081 | 5.60 | 45.39 | 23.6 | 165.8 | 142.2 |
| Farmer J | Komal peas-10 | 0.0087 | 5.01 | 43.43 | 28.5 | 48.9 | 20.4 |
| Farmer K | Komal peas-10 | 0.0068 | 11.50 | 78.21 | 48.9 | 168.4 | 119.4 |
| Farmer L | Komal peas-10 | 0.0147 | 5.87 | 86.37 | 28.9 | 116.6 | 87.7 |
| Mean | | | 6.99 | 63.35 | 32.5 | 124.9 | 92.4 |

TABLE 8A Wilcoxon (Kruskal-Wallis test) scores for Yield t/ha and Net income/ha for garden pea varieties in the medium lowlands in Talaburu.

| Yield (t/ha) | | | | | Net income/ha | | | |
|---|---|---|---|---|---|---|---|---|
| TRT | Sum of scores | Mean score | Chisq | Prob > Chisq | Sum of scores | Mean score | Chisq | Prob > Chisq |
| GS-10 | 20 | 5.00 | 1.38 | 0.5004 | 21 | 5.25 | 0.81 | 0.668 |
| KSP-110 | 32 | 8.00 | | | 30 | 7.50 | | |
| Komal | 26 | 6.50 | | | 27 | 6.75 | | |

TABLE 9 Income generated from intercropping French bean and yard long bean with maize in Churinsara during 2014.

| Replication | Area (ha) | Maize plot yield (kg) | French bean plot yield (kg) | Yard long bean plot yield (kg) | Yield (t/ha) | Cost (INR 1,000/ha) | Income (INR 1,000/ha) | Net income (INR 1,000/ha) |
|---|---|---|---|---|---|---|---|---|
| Maize + legume | | | | | | | | |
| Farmer A | 0.06 | 1,008.00 | 36.8 | | 17.50 | 32.1 | 152.8 | 120.7 |
| Farmer B | 0.02 | 313.50 | | | 12.67 | 35.1 | 101.3 | 66.2 |
| Farmer C | 0.02 | 317.33 | | | 15.56 | 41.5 | 124.4 | 83.0 |
| Farmer D | 0.03 | 465.23 | 15.7 | | 14.67 | 43.3 | 125.5 | 82.2 |
| Farmer E | 0.02 | 427.61 | 18.7 | | 19.17 | 55.1 | 170.7 | 115.6 |
| Farmer F | 0.02 | 406.92 | 23.1 | 8.4 | 16.30 | 58.8 | 157.7 | 98.9 |
| Farmer G | 0.05 | 872.08 | 42.1 | | 19.17 | 37.8 | 174.9 | 137.1 |
| Farmer H | 0.04 | 656.27 | 53.4 | | 15.33 | 46.4 | 148.3 | 101.9 |
| Farmer I | 0.06 | 689.17 | 14.9 | 2.5 | 12.00 | 33.9 | 102.0 | 68.1 |
| Farmer J | 0.03 | 348.33 | | | 12.67 | 45.1 | 101.3 | 56.2 |
| Farmer K | 0.03 | 473.73 | 25.1 | | 14.67 | 43.9 | 130.9 | 87.0 |
| Farmer L | 0.04 | 734.07 | 29.7 | | 18.33 | 49.6 | 161.5 | 111.9 |
| Mean | | 559.35 | 28.83 | 5.45 | 15.67 | 43.5 | 137.6 | 94.1 |
| Maize | | | | | | | | |
| Farmer M | 0.02 | 315.21 | | | 13.89 | 24.2 | 84.2 | 60.0 |
| Farmer N | 0.01 | 196.33 | | | 13.89 | 39.4 | 68.9 | 29.5 |
| Farmer O | 0.02 | 301.00 | | | 15.56 | 28.7 | 92.6 | 63.9 |
| Farmer P | 0.02 | 222.33 | | | 13.89 | 29.9 | 78.4 | 48.5 |
| Farmer Q | 0.02 | 366.54 | | | 15.00 | 28.9 | 88.1 | 59.3 |
| Farmer R | 0.02 | 323.40 | | | 15.00 | 24.9 | 92.1 | 67.3 |
| Farmer S | 0.02 | 244.44 | | | 13.89 | 29.7 | 78.6 | 48.8 |
| Mean | | 281.32 | | | 14.44 | 29.4 | 83.3 | 53.9 |

TABLE 9A Wilcoxon (Kruskal-Wallis test) scores for Yield t/ha and Net income/ha for intercropping French bean and yard long bean with maize in Churinsara during 2014.

| Yield (t/ha) | | | | | Net income/ha | | | |
|---|---|---|---|---|---|---|---|---|
| TRT | Sum of scores | Mean score | Chisq | Prob > Chisq | Sum of scores | Mean score | Chisq | Prob > Chisq |
| Maize + legume | 133.5 | 11.13 | 1.32 | 0.251 | 157 | 13.08 | 9.78 | 0.002 |
| Maize | 56.5 | 8.07 | | | 33 | 4.71 | | |

activities of research, we assume they have developed the capacity to identify solutions or alternatives through the internal and stakeholder linkages which were created as a platform by this project. Through the project the farmers were trained to mitigate the risk of growing the alternative crops. For instance, growing tomatoes during hot-wet season will be at risk of bacterial wilt and leaf diseases such as early and late blight. In that case, the farmers are able to contact the appropriate agencies to solve the problems, such as use of vegetable grafting with disease resistant rootstocks and scions to grow tomato in hot wet season. For cucurbits, the potential risk will be the fruit flies which can be managed by applying appropriate good agricultural practices including the fruit

**TABLE 9B** Income generated from intercropping legumes with maize in Churinsara during 2015.

| Farmer | Maize Plot yield (kg) | Maize yield (t/ha) | French bean yield (kg/plot) | Cost (INR 1,000/ plot) | Cost (INR 1,000/ ha) | Income (INR 1,000/ Plot) | Income (INR 1,000/ ha) | Net income (INR 1,000/ ha) | French bean yield (t/ha) | Labor day per ha | Total labor cost (INR 1,000/ ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Maize + legume | | | | | | | | | | | |
| Farmer A | 275 | 4.77 | 0.00 | 2.5 | 43.7 | 5.3 | 91.5 | 47.9 | 0.00 | 144 | 14.4 |
| Farmer B | 115 | 4.66 | 8 | 0.8 | 33.3 | 2.5 | 99.2 | 65.9 | 0.31 | 139 | 13.9 |
| Farmer C | 162 | 3.73 | 0.00 | 1.5 | 34.6 | 3.2 | 73.3 | 38.7 | 0.00 | 158 | 15.8 |
| Farmer D | 99 | 3.96 | 17 | 1.0 | 38.9 | 2.4 | 98.0 | 59.1 | 0.68 | 198 | 19.8 |
| Farmer E | 156 | 3.43 | 12 | 1.6 | 34.8 | 3.4 | 75.1 | 40.3 | 0.26 | 162 | 16.2 |
| Farmer F | 173 | 4.04 | 37 | 2.2 | 51.9 | 4.5 | 104.8 | 52.9 | 0.86 | 175 | 17.5 |
| Farmer G | 129 | 4.00 | 25 | 1.3 | 39.2 | 3.3 | 101.3 | 62.0 | 0.77 | 176 | 17.6 |
| Mean | 158 | 4.08 | 22.75 | 1.6 | 39.5 | 3.5 | 91.9 | 52.4 | 0.59 | 165 | 16.3 |
| Maize | | | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | | 0.0 |
| Farmer H | 58 | 2.57 | | 0.6 | 24.9 | 1.1 | 50.5 | 25.6 | | 150 | 15.0 |
| Farmer I | 51 | 2.09 | | 0.8 | 33.9 | 1.0 | 41.4 | 7.6 | | 175 | 17.5 |
| Farmer J | 39 | 2.23 | | 0.8 | 46.0 | 0.8 | 46.5 | 0.5 | | 183 | 18.3 |
| Mean | 50 | 2.29 | | 0.7 | 34.9 | 1.0 | 46.1 | 11.2 | | 169 | 16.8 |

Price (INR): French bean = 15–20/kg; maize green cob = 10–12/kg; maize dried grain = 15/kg; maize straw = 1.5/kg.

**TABLE 9C** Wilcoxon (Kruskal-Wallis test) scores for Yield t/ha and Net income/ha for intercropping legumes with maize in Churinsara during 2015.

| Yield (t/ha) | | | | | Net income/ha | | | |
|---|---|---|---|---|---|---|---|---|
| TRT | Sum of scores | Mean score | Chisq | Prob > Chisq | Sum of scores | Mean score | Chisq | Prob > Chisq |
| Maize + legume | 49 | 7.00 | 5.78 | 0.017 | 49 | 7.00 | 5.78 | 0.017 |
| Maize | 6 | 2.00 | | | 6 | 2.00 | | |

fly lures. This study and learnings by farmers will help them in trying not only vegetables but also newer crops with economic potential such as orchard crops, and plantation crops. The policies of the local government also influence the crop diversification with high value crops such as vegetables (Panda, 2014). Some studies also reported that the farmers shifting from growing vegetables to oilseeds due to the increased input and risk in growing vegetables (Singh et al., 2022).

However, while the agronomic and household nutrition results are very important and significant, given that agriculture remains the main livelihood in these communities, an even more important and significant aim was to explore how engaging farmers as partners in agronomic research could empower them and develop their capacity for solving problems. In this research the agronomic experimentation provides a highly relevant context for development of human capacity for local, independent innovation, aimed at improving livelihoods. The farmers were able to establish and conduct the experiments with sufficient rigor, supported by their peers in the SHG's and the project staff. In doing so the farmers generated new knowledge and developed new skills, sufficient to assist in the solution of new problems which might arise in the future. Such participatory action learning in SHG's with tribal women in the region has previously been shown to be effective in improving nutritional (Kadiyala et al., 2021) and health (Gope et al., 2019) outcomes for infants, but this appears to be the first time that such an approach has been successfully used by tribal farmers in India to conduct scientifically validated experiments. While only literate farmers were able to take and record measurements, substantial and effective peer to peer learning about the conduct of the research and the results were observed and discussed by all of the farmers in the SHG's. It has been demonstrated many times that peer-peer learning is more effective for technology adoption among rural poor than traditional extension approaches (BenYishay and Mobarak, 2019; Takahashi et al., 2020). Even in these highly disadvantaged communities, is it possible that empowerment and agency, through active participation in research, widens the pathway out of poverty? Although similar types of participatory approaches have been used elsewhere in the world with disadvantaged smallholders to tackle environmental degradation in agriculture (Johnson et al., 2003) and rice culture (Stoop et al., 2009), these approaches are not always successful (Nederlof and Dangbégnon, 2007). Much of the success of the present project lay in the common goal of the project team and farmers as systemic and positive change agents in the social, psychological and economic condition of the women farmers so they could take charge of their lives and engage with the world around them. The adoption of this common goal was a key element in the success of the project, more so than the agronomic technologies.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

RM, RMN, MU, and WB designed the study. DK and RM designed field sampling procedures, which were conducted by AK, BG and led by DK. AV and AR performed data analysis. RM, DK, and MU primarily wrote the manuscript with specific sections contributed by other authors. All authors contributed to the article and approved the submitted version.

## Funding

This work was undertaken as part of the initiative "Improving livelihoods with innovative cropping systems on the East India Plateau" which was supported by the Government of Australia. It was also supported by long-term strategic donors to the World Vegetable Center: Taiwan, the Foreign, Commonwealth and Development Office (FCDO) from the UK Government, United States Agency for International Development (USAID), Australian Centre for International Agricultural Research (ACIAR) (LWR/2010/082), Germany, Thailand, Philippines, Korea, and Japan.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.966376/full#supplementary-material

## References

Anuja, A., Kumar, A., Saroj, S., and Singh, K. (2020). The impact of crop diversification towards high-value crops on economic welfare of agricultural households in eastern India. *Curr. Sci.* 118:1575. doi: 10.18520/cs/v118/i10/1575-1582

Anuja, A., Shivaswamy, G., Ray, M., and Singh, K. (2022). Pattern of crop diversification and its implications on undernutrition in India. *Curr. Sci.* 122:1154. doi: 10.18520/cs/v122/i10/1154-1160

BenYishay, A., and Mobarak, A. M. (2019). Social learning and incentives for experimentation and communication. *Rev. Econ. Stud.* 86, 976–1009. doi: 10.1093/restud/rdy039

Bhasin, V. (2007). Status of tribal women in India. *Stud. Home Comm. Sci.* 1, 1–16. doi: 10.1080/09737189.2007.11885234

Birthal, P. S., Roy, D., and Negi, D. S. (2015). Assessing the impact of crop diversification on farm poverty in India. *World Dev.* 72, 70–92. doi: 10.1016/j.worlddev.2015.02.015

Chinnadurai, M., Karunakaran, K., Chandrasekaran, M., Balasubramanian, R., and Umanath, M. (2016). Examining linkage between dietary pattern and crop diversification: an evidence from Tamil Naidu. *Agric. Econ. Res. Rev.* 29, 149–160. doi: 10.5958/0974-0279.2016.00042.2

Cornish, P. S., Karmakar, D., Kumar, A., Das, S., and Croke, B. (2015). Improving crop production for food security and improved livelihoods on the East India plateau. I. Rainfall-related risks with rice and opportunities for improved cropping systems. *Agric. Syst.* 137, 166–179. doi: 10.1016/j.agsy.2015.01.008

Cornish, P., Kumar, A., and Khan, M. (Eds.) (2010). East India plateau - basket case or future food basket? Food Security from Sustainable Agriculture: Proceedings of the 15th Australian Agronomy Conference. Lincoln: Australian Society of Agronomy.

Dalal, S., and Shankar, T. (2022). Crop diversification and its importance in agriculture: a review. *Indian J. Nat. Sci.* 13, 44540–44548.

Das, B., and Tarai, D. (2011). Decision-making and fertility behaviour: a comparative analysis of scheduled caste and scheduled tribe women in Odisha. *Soc. Change* 41, 233–249. doi: 10.1177/0049085711041002

Debnath, A., and Bhattacharjee, N. (2016). Understanding malnutrition of tribal children in India: the role of women's empowerment. *Ecol. Food Nutr.* 55, 508–527. doi: 10.1080/03670244.2016.1223652

Dixit, R. (2010). Naxalite movement in India: the state's response. *J. Def. Stud.* 4, 21–35.

Farnworth, C., and Hutchings, J. (2009). *Organic agriculture and women's empowerment*. Chicester: IFOAM.

Gomes, J. F. (2015). The political economy of the Maoist conflict in India: an empirical analysis. *World Dev.* 68, 96–123. doi: 10.1016/j.worlddev.2014.11.021

Gope, R. K., Tripathy, P., Prasad, V., Pradhan, H., Sinha, R. K., Panda, R., et al. (2019). Effects of participatory learning and action with women's groups, counselling through home visits and crèches on undernutrition among children under three years in eastern India: a quasi-experimental study. *BMC Public Health* 19, 1–15. doi: 10.1186/s12889-019-7274-3

Joshi, P. K., Joshi, L., and Birthal, P. S. (2006). Diversification and its impact on smallholders: evidence from a study on vegetable production. *Agric. Econ. Res. Rev.* 19, 219–236.

Johnson, N. L., Lilja, N., and Ashby, J. A. (2003). Measuring the impact of user participation in agricultural and natural resource management research. *Agric. Syst.* 78, 287–306. doi: 10.1016/S0308-521X(03)00130-6

Kadiyala, S., Harris-Fry, H., Pradhan, R., Mohanty, S., Padhan, S., Rath, S., et al. (2021). Effect of nutrition-sensitive agriculture interventions with participatory videos and women's group meetings on maternal and child nutritional outcomes in rural Odisha, India (UPAVAN trial): a four-arm, observer-blind, cluster-randomised controlled trial. *Lancet Planet. Health* 5, e263–e276. doi: 10.1016/s2542-5196(21)00001-2

Keshri, K., and Bhagat, R. B. (2012). Temporary and seasonal migration: regional pattern, characteristics and associated factors. *Econ. Polit. Wkly.* 47, 81–88.

Kleinhenz, V., Schnitzler, W., and Midmore, D. (1996). Diversification and transformation of Asian paddy rice fields to upland vegetable production. *Plant Res. Dev.* 43, 81–94.

Kshatriya, G. K., and Acharya, S. K. (2016). Gender disparities in the prevalence of undernutrition and the higher risk among the young women of Indian tribes. *PLoS One* 11:e0158308. doi: 10.1371/journal.pone.0158308

Kumar, S. S. (2015). Nonviolent measures to Deal with Naxalism in India: an assessment of Government's response. *Thammasat Rev* 18, 84–101.

Mitra, S. (2017). Re-assessing "trickle-down" using a multidimensional criteria: the case of India. *Soc. Indic. Res.* 136, 497–515. doi: 10.1007/s11205-017-1568-6

Mukherjee, A. (2015). "Evaluation of the policy of crop diversification as a strategy for reduction of rural poverty in India" in *Poverty reduction policies and practices in developing Asia*. eds. A. Heshmati, E. Maasoumi and G. Wan (Switzerland: Asian Development Bank and Springer International Publishing AG), 125–143.

Nederlof, E. S., and Dangbégnon, C. (2007). Lessons for farmer-oriented research: experiences from a west African soil fertility management project. *Agric. Hum. Values* 24, 369–387. doi: 10.1007/s10460-007-9066-0

Panda, R. K. (2014). "Trend and pattern of crop diversification in Odisha" in *India studies in business and economics*. eds. M. Ghosh, D. Sarkar and B. Roy (New Delhi: Springer), 59–67.

Petare, K. J., Nayak, J., Jaini, V., and Wani, S. P. (2016). Livelihood system assessment and planning for poverty alleviation: a case of rainfed agriculture in Jharkhand. *Curr. Sci.* 110, 1773–1783. doi: 10.18520/cs/v110/i9/1773-1783

Rajendran, S., Afari-Sefa, V., Shee, A., Bocher, T., Bekunda, M., Dominick, I., et al. (2017). Does crop diversity contribute to dietary diversity? Evidence from integration of vegetables into maize-based farming systems. *Agric Food Sec* 6:50. doi: 10.1186/s40066-017-0127-3

Ravishankar, M., Kaur, D. P., Bhushan, K. B., and Easdown, W. J. (2015). Traditional leafy vegetables of a tribal community in Jharkhand, India. *Acta Hortic.* 43–52, 43–52. doi: 10.17660/actahortic.2015.1102.4

SAS Institute Inc. (2018). *SAS/STAT® 15.1 User's guide*. Cary, NC: SAS Institute Inc.

Shah, A. (2006). The labour of love. Seasonal migration from Jharkhand to the brick kilns of other states in India. *Contrib. Indian. Sociol.* 40, 91–118. doi: 10.1177/006996670504000104

Shah, A. (2007). "Keeping the state away": democracy, politics, and the state in India's Jharkhand. *J. R. Anthropol. Inst.* 13, 129–145. doi: 10.1111/j.1467-9655.2007.00417.x

Singh, R. D. (2010). "Food security for increasing rural livelihood under limited water supply through adoption of diversified crops and crop sequences" in *Resource conservation Technologies for Food Security and Rural Livelihood*. eds. A. R. Khan, S. S. Singh, R. C. Bharti, T. K. Srivastava and M. A. Khan (Udaipur, India: Agrotech Publishing Academy), 342–355.

Singh, B. (n.d.) Status paper on rice in Jharkhand. Directorate of Rice Research. http://forest.jharkhand.gov.in/fresearch/admin/file/research_665.pdf (Accessed November 22, 2021).

Singh, P., Adhale, P., Guleria, A., Bhoi, P. B., Bhoi, A. K., Bacco, M., et al. (2022). Crop diversification in South Asia: a panel regression approach. *Sustainability* 14:9363. doi: 10.3390/su14159363

Stoop, W. A., Adam, A., and Kassam, A. (2009). Comparing rice production systems: a challenge for agronomic research and for the dissemination of knowledge-intensive farming practices. *Agric. Water Manag.* 96, 1491–1501. doi: 10.1016/j.agwat.2009.06.022

Takahashi, K., Muraoka, R., and Otsuka, K. (2020). Technology adoption, impact, and extension in developing countries' agriculture: a review of the recent literature. *Agric. Econ.* 51, 31–45. doi: 10.1111/agec.12539

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 May 2023
DOI 10.3389/fsufs.2023.1150242

EDITED BY
Rupak Goswami,
Ramakrishna Mission Vivekananda Educational and Research Institute, India

REVIEWED BY
Vengadeshvaran Sarma,
Nottingham University Business School, Malaysia
Shinoj Parappurathu,
Central Marine Fisheries Research Institute (ICAR), India

*CORRESPONDENCE
Yunhee Kang
✉ ykang12@jhu.edu

RECEIVED 23 January 2023
ACCEPTED 12 April 2023
PUBLISHED 12 May 2023

CITATION
Kang Y, Wabyona E, Udahemuka FR, Traore A and Doocy S (2023) Economic impact of COVID-19 on income and use of livelihoods related coping mechanisms in Chad. *Front. Sustain. Food Syst.* 7:1150242.
doi: 10.3389/fsufs.2023.1150242

# Economic impact of COVID-19 on income and use of livelihoods related coping mechanisms in Chad

Yunhee Kang[1]*, Edgar Wabyona[2], Francois Regis Udahemuka[2], Alladari Traore[2] and Shannon Doocy[1]

[1]Department of International Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, United States, [2]World Food Programme Chad—N'Djamena, N'Djamena, Chad

**Introduction:** Impacts of the economic slowdown due to COVID-19 were prevalent in SubSaharan African countries. Using four nationally representative surveys collected in 2020 (rural $n$=13,208; urban $n$=1736) and 2021 ($n$=14,730; $n$=2,231), this secondary analysis evaluates economic impacts of the pandemic on household income and use of livelihoods-related coping mechanisms in Chad.

**Methods:** Univariate and multivariate regression, accounting for the survey design and sampling weights, was used to examine risk factors for reported income reduction and coping mechanism use and the associations with food expenditures and food security.

**Results:** The economic impact of COVID-19 was greater in urban areas than rural areas in 2020 with improvement in urban areas and deterioration in rural areas in 2021. The reported income reduction was associated with female and unmarried household heads, living in the Saharan zone, and in rural areas, non-agricultural income sources. In urban areas, having skilled/unskilled labor as the primary income source was protective. Risk factors for the adoption of livelihoods-related coping mechanisms were similar to those of income reduction, with findings related to poor living conditions. Income reduction due to COVID-19 was associated with the use of stress and crisis coping strategies and lower household expenditure in both years and poor food consumption in rural areas in 2020.

**Discussion:** This study elucidates the potential impact pathways of COVID-19 from a household economic downturn to limited food spending, poor food consumption, and increased use of coping mechanisms. Findings are relevant for informing the targeting of assistance in future economic shocks and suggest prioritizing socioeconomically vulnerable households.

KEYWORDS

**COVID-19, Chad, income, household economy, food security, coping mechanism**

## 1. Introduction

There has been a marked decline in global food security triggered by recent COVID-19-related lockdowns and supply chain disruptions that led to decreases in household income and purchasing power in many countries (Workie et al., 2020; Béné et al., 2021). This situation has led to a surge in the global malnourished population. Around 2.3 billion people were moderately or severely food insecure in 2021, and 11.7% percent of the global population faced severe food insecurity (FAO, IFAD, UNICEF, WFP, and WHO, 2022). According to the Food and Agriculture Organization of the United Nations (FAO), after increasing sharply in 2020, the global prevalence of moderate or severe food insecurity remained mostly unchanged in 2021, but severe food insecurity rose higher, reflecting a deteriorating situation for people already facing serious hardships (FAO, IFAD, UNICEF, WFP, and WHO, 2022).

Differential vulnerability linked to COVID-19 disruptions was more apparent in lower- and middle-income countries (LMICs) where impoverished populations have less access to social safety net programs and were more likely to be food insecure at the onset of the pandemic than in high-income countries (Arndt et al., 2020; Buheji et al., 2020; Chirisa et al., 2022). For example, urban populations were more likely to lose employment and have reduced income than the rural population in the Asia Pacific region, and low-income households faced elevated risk of economic loss than higher-income groups (Kang et al., 2021; Padmaja et al., 2022). Similarly, the reduction in food expenditures in 2020 was higher in urban areas in Bangladesh, India and Myanmar, suggesting that both household economic and food insecurity impacts of the pandemic were more extensive in urban areas than rural areas during the first year of the pandemic (Kang et al., 2021). In Sub-Saharan Africa, a multi-country study found that female-headed households, those having less-formal education and in lower economic groups were more vulnerable to food insecurity (Dasgupta and Robinson, 2021; Negesse et al., 2022). In 2020 only, women lost more than 64 million jobs disproportionally compared to men (80 million) (International Labor Organization, 2021). Largely, women have low wages and informal jobs, and were less likely to have institutional support (Shahidul and Mostafa, 2021). At a regional level in Sub-Saharan Africa, female-headed households were at higher risk of income loss due to a lack of control over financial and social-capital resources during the pandemic (Dasgupta and Robinson, 2021) and socio-economically disadvantaged groups have also been observed as more severely impacted (Burström and Tao, 2020; Macharia et al., 2021).

A landlocked Sahelian country in Africa, Chad is among the least developed countries, ranking 187 out of 189 on the Human Development Index in 2019. Although the country has made progress on poverty reduction, the population living below the poverty line increased from 4.7 million in 2011 to 6.5 million in 2018 (World Bank, 2022a). The first case of COVID-19 in Chad was detected on March 5, 2020 and 7,696 infections and 194 coronavirus-related deaths had been reported by Apr 19, 2023 (WHO, 2023). Following this onset, and in line with global trends and practices, Chad declared a health emergency and imposed a series of COVID-19 prevention measures throughout the rest of 2020 and 2021. These included the closure of borders and businesses, restricted movements between regions, and the implementation of curfews among others (Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD, 2022).

Similar to other Sahelian countries, the Government in Chad alongside humanitarian and development partners has fairly well-established systems to respond to the [recurrent] shocks and vulnerabilities that result from the confluence of structural poverty, conflict, climate change, and limited economic opportunities. However, there is a paucity of studies characterizing the economic impact of COVID-19 on food security and livelihoods in Chad (Mennechet and Dzomo, 2020; Tchana Tchana et al., 2022). In consequence, responses to such pandemic threats are not fully adapted to address the needs that arise. Since the likelihood of pandemics has increased over the past century and will likely continue or intensify (Patel et al., 2015), and given the variable impact of COVID-19 disruptions, this analysis sought to characterize changes in household economy during the onset of the COVID-19 pandemic among households in Chad to fill the existing knowledge gap.

The analysis used nationally representative household survey data to examine the economic impacts of COVID-19 among the population in Chad. Specifically, the study sought to identify risk factors for income loss due to COVID-19 and the use of crisis and emergency coping mechanisms; and to examine associations between income change due to COVID-19 and coping strategy use, short and long-term expenditures, and food consumption. Identifying population sub-groups that are particularly vulnerable to economic hardship and financial strain related to the indirect effects of the COVID-19 pandemic can inform humanitarian and development [policy] responses in future pandemics and contribute to a broader understanding of how economic disruptions differentially impact vulnerable populations in Chad and beyond.

## 2. Methods

The analysis is based on secondary datasets of the "Enquête Nationale sur la Sécurité Alimentaire" or National Food Security Assessments, hereafter referred to as ENSA. The ENSA survey is representative at the admin 2 (department) level and has been conducted annually since 2016 with nation-wide coverage (that is, conducted in all departments). The ENSA is organized by a specialized institution of the Government of Chad in partnership with WFP, FAO among other institutions. The full ENSA methodology is described elsewhere (Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD, 2020). However, in brief, a two-stage probabilistic cluster sampling methodology was used to select villages and households within each of the 68 departments [which served as strata] and N'Djamena. In 2020, data collection was conducted from October 17 to November 3, 2020, in rural areas and October 15 to November 27 in N'Djamena. Data collection spanned a similar period in 2021 and was conducted between October 3 and November 12 in rural areas, and October 7 to November 18 in N'Djamena. The total sample size was 13,208 households in 2020 and 14,730 households in 2021 in rural areas, while that in the urban (N'Djamena) surveys was 1,736 households in 2020 and 2,231 households in 2021.

The questionnaires covered a variety of topics such as sociodemographic characteristics, household assets, agricultural practices, sources of income, level of food stocks, food consumption, expenditures, household shocks, and coping mechanisms. Data from ENSA 2020 was considered 'early COVID,' and data from ENSA 2021 was considered 'during COVID,' with COVID questions included in both time sets. Key variables of focus for this analysis included perceived income change, use of livelihoods-related coping mechanisms, food consumption and household food expenditures. Income change due to COVID-19 was assessed as a categorical variable comparing the change in revenues in the preceding 3 months to the same period last year and was re-coded to a dichotomous variable (no change/increased vs. decreased) for analysis. Use of livelihoods-related coping mechanisms within the past month was collected using the Livelihoods Coping Strategies Index (LCSI) (WFP VAM resource center, 2021) and was categorized into three levels of severity: (1) stress coping mechanisms (non-productive asset sales, livestock sales, buying/borrowing food on credit and spending savings); (2) crisis coping mechanisms (harvesting immature crops, removing children from school, and reducing health and/or education spending); and (3) emergency coping mechanisms (sending household members for begging; selling the last breeding livestock and selling land). The LCSI was then calculated for each household using weighting by severity level and summing all coping mechanisms adopted. Food Consumption Score (FCS) is a standard indicator that reflects the diversity and frequency of household food consumption in the preceding week (Wiesmann et al., 2009); foods are categorized into eight groups, weighted according to nutritional value, and summed to calculate the FCS; households are then grouped into two food consumption group (poor/borderline vs. acceptable) based on pre-determined thresholds. Finally, household expenditure variables included household expenses in the short-term (preceding month) and long-term (6 months), and the proportion of food expenses of total household expenditures.

Using the October 2020 and 2021 ENSA datasets, this analysis sought to identify spatial–temporal trends and factors associated with the household economy and food security during COVID-19 separately in rural and urban areas. Statistical analysis was conducted using STATA/SE 17.0 (Stata Corporation, College Station, TX, United States). All analyses accounted for survey design and sampling weights. Point estimates and 95% confidence interval were generated for independent and dependent variables, and are presented for urban and rural locations, agro-ecological zones (Saharan, Sahelian, and Sudanian: Figure 1); and wealth quintiles, which were generated using propensity score analysis based on asset variables. Univariate logistic regression was conducted to test the association between each of the potential risk factors and outcome variables (income change due to COVID-19, crisis and emergency coping mechanism use), and if the value of $p$ was <0.10 the variable was included in the multivariate logistic regression analysis. The variables that presented significance ($p < 0.05$ or 95%CI not including 1.0) were considered significant risk factors. Predictor characteristics to be tested for the association with outcome variables included socioeconomic characteristics (i.e., age, gender, marital status, literacy, occupation), household composition (i.e., size, disability, and chronic disease status of family members) and living conditions (i.e., dwelling type, water, energy and cooking source), and agroecological zone. Additionally, the association between change in income due to COVID-19 (no change/increased vs. decreased) and food security outcome variables such as coping strategy use, household expenditures, and food consumption were explored using income change due to COVID-19 as the independent variable. Dependent variables are the use of any stress and/or emergency coping mechanisms, short and long-term food expenditures, and food consumption (poor/borderline vs. acceptable). Linear regression was used to test the association between income due to COVID-19 and short and long-term food expenditures (continuous variables). Expenditure distributions were right-skewed, necessitating log-transformation. Demographic and socio-economic variables were accounted for in the adjusted regression analysis and included residence location (agroecological zone) and household characteristics. The association between household income change due to COVID-19 and expenditures was not tested in urban areas in 2021 due to a small sample size.

The study was determined to be exempt by the Johns Hopkins Bloomberg School of Public Health Institutional Review Board review because it involved secondary analysis of anonymized data.

## 3. Results

Analysis of ENSA data is presented separately for urban and rural areas for both October/November 2020 (early COVID period) and October/November 2021 (COVID period).

### 3.1. Household demographic characteristics

Household demographic characteristics are summarized in Table 1. The average household size was 7 in both N'Djamena and rural areas, and 39.4–44.2% of households were classified as large households, which were defined as ≥8 members. Polygamous households were more frequent in rural areas (26.7–28.7%) as compared to N'Djamena (15.2–16.9%), while N'Djamena households were more likely than rural households to be female-headed (38.7–39.4% vs. 17.9–21.9%, respectively). Household head illiteracy was more prevalent in rural areas (62.7–63.3%) than in N'Djamena (38.7–39.4%). Almost all households had no use of electricity as an energy source in rural areas (0.1–0.2%) and most residences were built with brick and cement, with a higher percentage in N'Djamena. There were notable differences in the use of efficient cooking sources between urban areas (76.9–85.1%) and rural areas (0.2%); similarly, access to improved drinking water was higher in N'Djamena (≥99.7) as compared to rural areas (54.7–58.2%). In rural areas, nearly half of the sample came from Sahelian and Sudanian zone, whereas respondents from Saharan zone accounted for only 3.4 and 6.0% of the 2020 and 2021 samples, respectively.

### 3.2. Household economy

In rural areas, the primary income sources in 2020 were agriculture (33.4%), followed by skilled/unskilled artisanal labor (23.3%), livestock rearing (22.1%), and petty trade (13.2%), and this distribution was similar in 2021. In urban areas, approximately half of the households (51.1–54.8%) reported petty trade as their primary income source, followed by skilled/unskilled/artisanal labor (12.8–18.7%) and livestock sales (15.0–17.3%) (Table 2). In urban areas, 65.9% of households experienced income loss in 2020 and this proportion reduced to 57.6% in 2021. In rural areas, 61.1% of households experienced an income reduction due to COVID-19 in 2020, and this figure increased to 66.7% in 2021. When assessed by zone, the proportion of households reporting decreased income due to COVID-19 was the largest in the Saharan zone in both 2020 and 2021. Interestingly, the proportion of households reporting COVID-19-related income reductions declined by 6.7% in the Saharan zone from 2020 to 2021 (Figures 2A,B), while increases of 4.7 and 6.7% of households reporting income loss were observed in the Sahelian and Sudanian zones, respectively. Approximately one-third of households in urban and rural areas in 2020 and in urban areas in 2021 reported a decrease in income sources (Figures 2C–F), whereas over half of rural households reported a decline in the number of income sources in 2021.

Opposite trends were observed in coping mechanism use in urban and rural areas from 2020 to 2021. Coping strategy adoption was greater in urban N'Djamena households in 2020, but by 2021

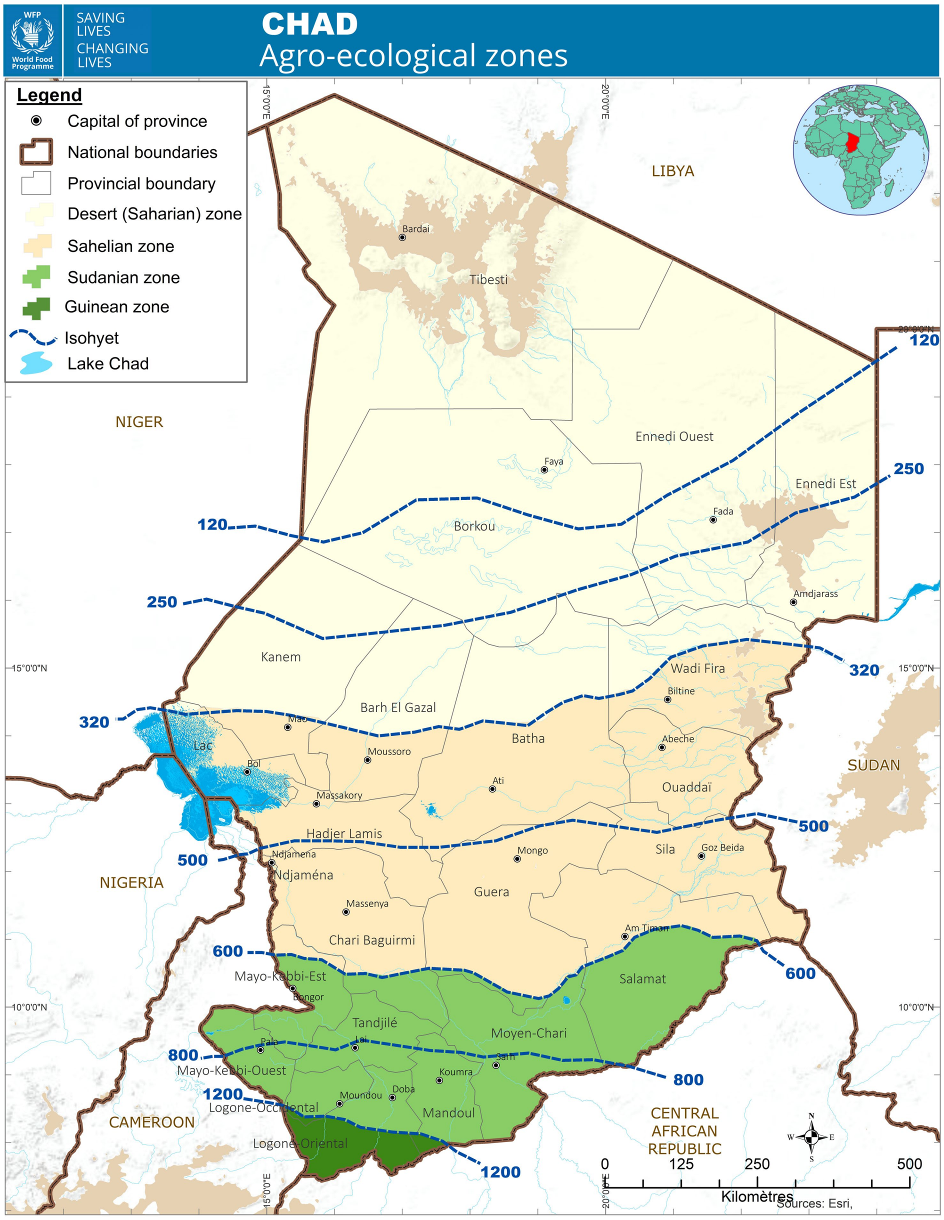


FIGURE 1
Map of Chad with zones. Obtained from WFP with appropriate permission.

a shift occurred where rural households were more likely to have adopted emergency and crisis level coping mechanism. The mean LCSI score in rural areas rose from 0.79 to 1.25 between 2020 and 2021, whereas in urban areas it declined from 0.98 to 0.59 (Table 2). In rural areas, the use of crisis-level coping mechanisms increased by 7.1% (from 11.7 to 18.8%) and emergency coping mechanism use increased by 3.5% (from 3.4 to 7.9%) from 2020 to 2021. Coping mechanism use was the greatest in the Saharan zone in both 2020 and 2021. In contrast to rural trends, urban areas saw reductions of 11.8% (from 20.2 to 8.4%) and 1.7% (from 3.2 to 1.5%) in crisis and emergency coping mechanism use, respectively. The use of coping mechanisms increased with decreasing wealth status (higher among poorer quintiles) (Figures 3A–F).

## 3.3. Risk factors for reduced income due to COVID-19

In rural areas, adjusted models showed that male-headed households and those reporting agriculture as the primary income source were less likely to report COVID-19 related income reductions in both 2020 and 2021 (Table 3). Among rural households in 2020, female headed households were more likely to experience income loss due to COVID-19 than male headed households (OR = 1.21, CI: 1.04, 1.41) and, compared to those who reported agriculture as a primary income source, those with other primary income sources were more likely to report COVID-19 related income losses (livestock OR = 1.61, CI: 1.16, 2.24; petty trade OR = 1.47, CI: 1.09, 1.98; skilled/unskilled labor OR = 1.37, CI: 1.03, 1.81); additionally, residence in the Saharan

TABLE 1 Sociodemographic characteristics of households participating in Chad ENSA surveys, 2020–2021.

| | Rural households | | Urban households | |
|---|---|---|---|---|
| | October 2020 | October 2021 | October 2020 | October 2021 |
| | *n* =13,208 | *n* =14,730 | *n* =1736 | *n* =2,231 |
| Household demographics | % (95%CI)[1] | % (95%CI)[1] | % (95%CI)[1] | % (95%CI)[1] |
| **Household size** | | | | |
| Mean (SE) | 7.1 (0.1) | 7.7 (0.1) | 7.7 (0.1) | 7.4 (0.7) |
| Large Households (8+ members) | 39.4 (36.9, 42.0) | 44.2 (41.3, 47.1) | 44.1 (41.8, 46.5) | 41.1 (39.1, 43.2) |
| **Household structure** | | | | |
| Monogamous | 62.3 (60.1, 64.3) | 62.3 (60.0, 64.6) | 60.6 (58.3, 62.8) | 64.6 (62.6, 66.6) |
| Polygamous | 26.7 (24.4, 29.0) | 28.7 (26.5, 31.0) | 16.9 (15.2, 18.8) | 15.2 (13.7, 16.7) |
| Divorced/widowed/single | 11.1 (9.8, 12.4) | 9 (7.7, 10.5) | 22.5 (20.6, 24.5) | 20.2 (18.6, 21.9) |
| **Household head characteristics** | | | | |
| Household head age | | | | |
| <25 years | 6.2 (5.6, 6.9) | 4.9 (4.2, 5.7) | 2.65 (1.99. 3.52) | 2.0 (1.5, 2.7) |
| 25–34 years | 23.8 (22.8, 24.8) | 22.4 (20.6, 24.) | 19.7 (17.9, 21.6) | 15.4 (14.0, 17.0) |
| 35–44 years | 25.7 (24.6, 26.8) | 28.5 (27.2, 29.8) | 29.7 (27.6, 31.9) | 32.1 (30.2, 34.1) |
| 45–54 years | 22.8 (21.7, 23.9) | 23.1 (21.8, 24.4) | 24.4 (22.5, 26.6) | 28.0 (26.1, 29.9) |
| ≥55 years | 21.5 (20.2, 22.9) | 21.2 (19.8, 22.5) | 23.6 (21.6, 25.6) | 22.5 (20.8, 24.2) |
| Female household head | 21.9 (19.6, 24.5) | 17.9 (15.1, 21.1) | 36.4 (34.2, 38.7) | 31.2 (29.3, 33.2) |
| Illiterate household head | 63.3 (58.8, 67.7) | 62.7 (58.3, 66.9) | 39.4 (37.1, 41.7) | 38.7 (36.7, 40.7) |
| Disabled household head | 10.2 (7.9, 13.2) | 8.3 (7.1, 9.7) | 8.53 (7.3, 9.9) | 10.6 (9.4, 11.9) |
| **Residence characteristics** | | | | |
| Residence location | | | | |
| Saharan zone | 3.4 (1.8, 6.4) | 6.0 (3.8, 9.5) | -- | -- |
| Sahelian zone | 46.4 (40.2, 52.7) | 46.3 (40.1, 52.6) | -- | -- |
| Sudanian zone | 50.2 (44.0, 56.4) | 47.7 (41.6, 53.8) | -- | -- |
| Living conditions[2] | | | | |
| Lighting source – electricity/ | 0.2 (0.1, 0.4) | 0.1 (0.0, 0.4) | 56.0 (53.7, 58.4) | 99.4 (98.9, 99.6) |
| Wall materials – brick/cement | 80.8 (75.7, 85.0) | 80.8 (74.7, 85.6) | 93.1 (91.8, 94.2) | 94.7 (93.7, 95.6) |
| Main cooking source – efficient | 0.2 (0.1, 0.4) | 0.2 (0.1, 0.6) | 76.9 (74.9, 78.8) | 85.1 (83.5, 86.5) |
| Drinking water source – improved | 54.7 (46.5, 62.5) | 58.2 (51.0, 65.1) | 99.9 (99.6, 99.9) | 99.7 (99.7, 99.9) |

[1]Weighted analysis; [2]Reference categories are other (fuel, wall material) or inefficient/unimproved (cooking, water source).

zone was at a higher risk for income loss as compared to the Sudanian zone (OR = 2.43, CI: 1.04, 5.68). Similar to findings in 2020, a higher risk of income loss in 2021 was experienced by female headed households (OR = 1.29, CI: 1.05, 1.58) and those where livestock rearing was the primary income source (OR = 1.37, CI: 1.05, 1.80) as compared to households engaged primarily in agriculture. Unexpectedly, income loss due to COVID-19 was less likely among households having an illiterate household head in rural areas in 2021 (OR = 0.82, CI: 0.68, 1.00).

There was less consistency in risk factors for COVID-19 related income loss between 2020 and 2021 in urban areas. During 2020, urban households were more likely to report income loss if they had a large household size (OR = 1.38, CI: 1.05, 1.82), had an unmarried household head (OR = 1.38, CI: 1.05, 1.82; reference monogamous married households). Poor quality housing materials (OR = 0.52, CI: 0.35, 0.77) and income source as skilled/unskilled/artisanal labor (OR = 0.59, CI: 0.40, 0.88) were negatively associated with losing income, however, not using electricity as a light source (OR = 1.60, CI: 1.26, 2.02) was positively associated with income loss. In 2021, risk factors associated with income loss in urban areas included being a female headed household (OR = 1.27, CI: 1.00, 1.62) and not using electricity as a light source (OR = 1.34, CI: 1.11, 1.63), whereas engagement in skilled/unskilled/artisanal labor continued to be protective against income loss (OR = 0.49, CI: 0.28, 0.84) compared to agriculture.

TABLE 2 Economic characteristics of households participating in Chad ENSA surveys, 2020–2021.

| | Rural households | | Urban households | |
|---|---|---|---|---|
| | October 2020 | October 2021 | October 2020 | October 2021 |
| | *n* =13,208 | *n* =14,730 | *n* =1,736 | *n* =2,231 |
| | % (95% CI)[1] | % (95% CI)[1] | % (95% CI)[1] | % (95% CI)[1] |
| **Household income** | | | | |
| COVID-related income change[1] | | | | |
| Increased | 17.1 (14.6, 20.0) | 10.7 (9.1, 12.7) | 5.2 (4.3, 6.4) | 4.7 (3.9, 5.7) |
| No change | 21.8 (18.4, 25.6) | 22.6 (19.3, 26.4) | 28.9 (26.8, 31.0) | 37.7 (35.7, 39.7) |
| Decreased | 61.1 (56.7, 65.3) | 66.7 (62.9, 70.2) | 65.9 (63.6, 68.1) | 57.6 (55.5, 59.6) |
| Change in number of income source[1] | | | | |
| Increased | 14.2 (12.0, 16.8) | 9.7 (8.0, 11.7) | 4.3% (3.5, 5.4) | 4.5 (3.7, 5.4) |
| No change | 49.9 (45.5, 54.2) | 55.7 (50.1, 61.0) | 64.6 (62.3, 66.7) | 44.2 (42.1, 46.3) |
| Decreased | 35.9 (31.8, 40.3) | 34.7 (29.4, 40.3) | 31.1 (29.0, 33.3) | 51.3 (49.2, 53.4) |
| Mean number of income sources | 1.88 (1.79, 1.98) | 1.85 (1.76, 1.95) | 1.38 (1.35, 1.41) | 1.51 (1.48, 1.53) |
| Primary income source in rural[2] | | | | |
| Agriculture | 33.4 (28.6, 38.5) | 38.5 (33.6, 43.5) | 9.7 (8.3, 11.2) | 3.1 (2.4, 3.9) |
| Livestock | 22.1 (18.8, 25.9) | 25.3 (20.9, 30.2) | 17.3 (15.6, 19.1) | 15.0 (13.6, 16.6) |
| Petty trade | 13.2 (11.3, 15.3) | 9.6 (7.9, 11.6) | 51.1 (48.7, 53.4) | 54.8 (52.7, 56.9) |
| Skilled/unskilled/artisanal labor | 23.3 (20.4, 26.4) | 21.8 (18.8, 25.2) | 12.8 (11.4, 14.5) | 18.7 (17.1, 20.4) |
| Humanitarian aid/ Remittances | 4.4 (3.5, 5.6) | 2.8 (2.2, 3.6) | 3.2 (2.4, 4.1) | 3.0 (2.3, 3.7) |
| Others | 3.6 (2.6, 5.1) | 2.1 (1.6, 2.6) | 5.9 (4.9, 7.1) | 5.4 (4.6, 6.4) |
| **Livelihoods coping strategies use** | | | | |
| Livelihoods coping strategies index score[3] | 0.79 (0.61, 0.96) | 1.25 (1.00, 1.51) | 0.98 (0.90, 1.05) | 0.59 (0.53, 0.63) |
| Stress coping mechanisms use (any) | 28.2 (27.5, 29.0) | 31.9 (27.2, 36.9) | 35.8 (33.5, 38.1) | 31.4 (29.4, 33.3) |
| Sell non-productive goods | 5.4 (3.5, 8.3) | 8.1 (5.5, 11.6) | 24.5 (21.9, 27.3) | 16.5 (14.7, 18.5) |
| Buy/borrow food on credit | 19.0 (14.4, 24.5) | 24.1 (18.8, 30.4) | 27.0 (24.7, 29.5) | 8.3 (5.6, 12.2) |
| Spend savings | 13.8 (10.4, 18.0) | 24.8 (19.1, 31.6) | 19.2 (16.9, 21.8) | 11.0 (9.3, 13.0) |
| Livestock Sales | 11.4 (8.7, 14.7) | 24.4 (19.6, 30.0) | 12.5 (9.9, 15.7) | 26.0 (23.8, 28.3) |
| Crisis coping mechanism use (any) | 11.7 (11.1, 12.2) | 18.8 (15.3, 22.9) | 20.2 (18.2, 22.2) | 8.4 (7.3, 9.6) |
| Harvesting immature crops | 8.3 (5.5, 12.2) | 22.7 (17.9, 28.4) | -- | 8.6 (7.2, 10.1) |
| Remove children from school | 8.7 (6.3, 11.9) | 5.8 (4.0, 8.3) | 25.8 (23.3, 28.6) | 3.7 (2.7, 5.0) |
| Reduce health or education spending | 3.5 (2.0, 6.1) | 6.4 (3.9, 10.3) | 8.9 (6.7, 11.7) | 3.5 (2.7, 4.6) |
| Emergency coping mechanism use (any) | 3.4 (3.1, 3.8) | 7.9 (5.8, 10.8) | 3.2 (2.5, 4.2) | 1.5 (1.1, 2.1) |
| Send begged household members | 1.1 (0.6, 1.9) | 4.3 (2.5, 7.2) | 1.8 (1.1, 2.8) | 2.6 (1.7, 3.9) |
| Selling parcels of land | 1.6 (1.0, 2.5) | 8.8 (5.5, 13.9) | 3.7 (2.6, 5.2) | 0.32 (0.1, 0.9) |
| Selling the latest breeding livestock | 2.9 (1.8, 4.6) | 8.9 (6.4, 12.2) | 5.2 (3.3, 7.9) | 5.1 (2.7, 9.6) |

[1] Compared to previous year; [2] Included if reported as one of the top three household income sources; [3] Range 0–19, calculated using the WFP CARI method with weighting by severity level.

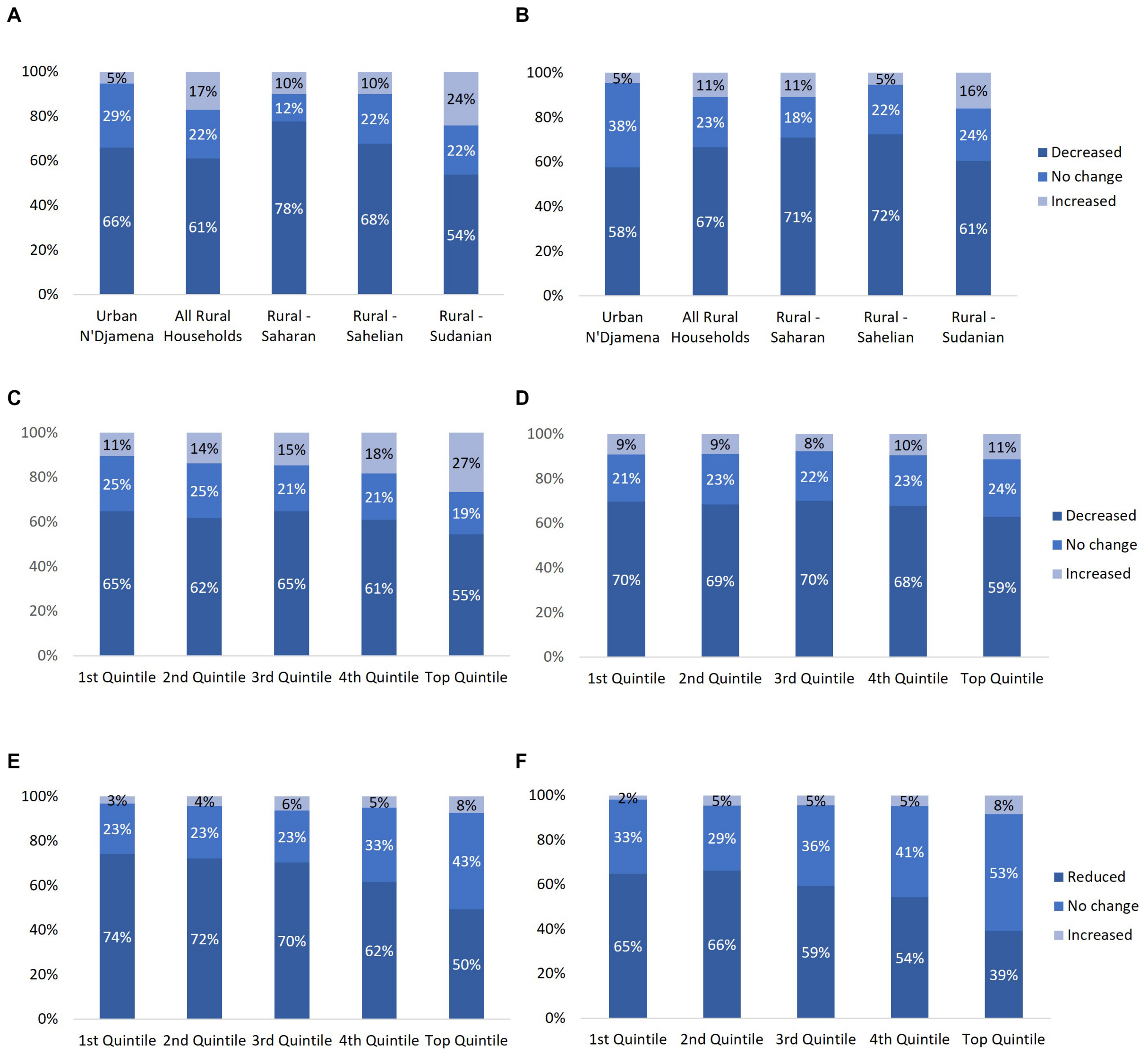


FIGURE 2
COVID-19 related income change by residence location and wealth quintile, 2020–2021. **(A)** By residence location in 2020; **(B)** by residence location in 2021; **(C)** by wealth quintile in rural 2020; **(D)** by wealth quintile in rural 2021; **(E)** by wealth quintile in N'Djamena 2020; **(F)** by wealth quintile in N'Djamena 2021.

## 3.4. Risk factors for crisis and emergency coping mechanism use

In rural areas of Chad during early COVID in 2020, having a non-agricultural primary income source (livestock rearing, [un] skilled labor, humanitarian aid, and others) was protective against the use of crisis and emergency level coping mechanisms (OR range: 0.32, 0.58) (Table 4). In contrast, female headed households (OR = 1.78, CI: 1.35, 2.35) and those with poor quality housing materials (OR = 2.10, CI: 1.36, 3.21) were more likely to adopt crisis or emergency level coping mechanisms in 2020. Later in the pandemic in 2021, the rural risk profile for coping mechanisms use changed, and both polygamous households (OR = 1.18, CI:1.00, 1.38) and unmarried household heads (OR = 1.53, CI: 1.19, 1.97) were more likely to have adopted crisis or emergency-level coping mechanisms compared to monogamous families, while female headed households had a marginally increased risk (OR = 1.20, CI: 0.99, 1.69, $p = 0.05$). Additionally, poor housing materials were associated with an increased risk of coping mechanism use in 2020 (OR = 2.10, CI: 1.36, 3.21). In contrast to 2020, poor quality housing was inversely associated with coping mechanism use (OR = 0.73; CI: 0.54, 0.99) in 2021.

In urban areas during 2020, households that were more likely to adopt crisis and emergency coping mechanisms included polygamous households (OR = 1.76, CI: 1.29, 2.42), those with illiterate household heads (OR = 1.34, CI: 1.03, 1.73) and those using inefficient cooking methods (OR = 1.45, CI: 1.08, 1.93); in contrast households with skilled/unskilled labor as a primary income source were less likely than those engaged in agriculture to adopt crisis or emergency coping mechanisms (OR = 0.53, CI: 0.35, 0.79) (Table 4). In 2021, there was little consistency in risk factors for coping mechanism adoption in

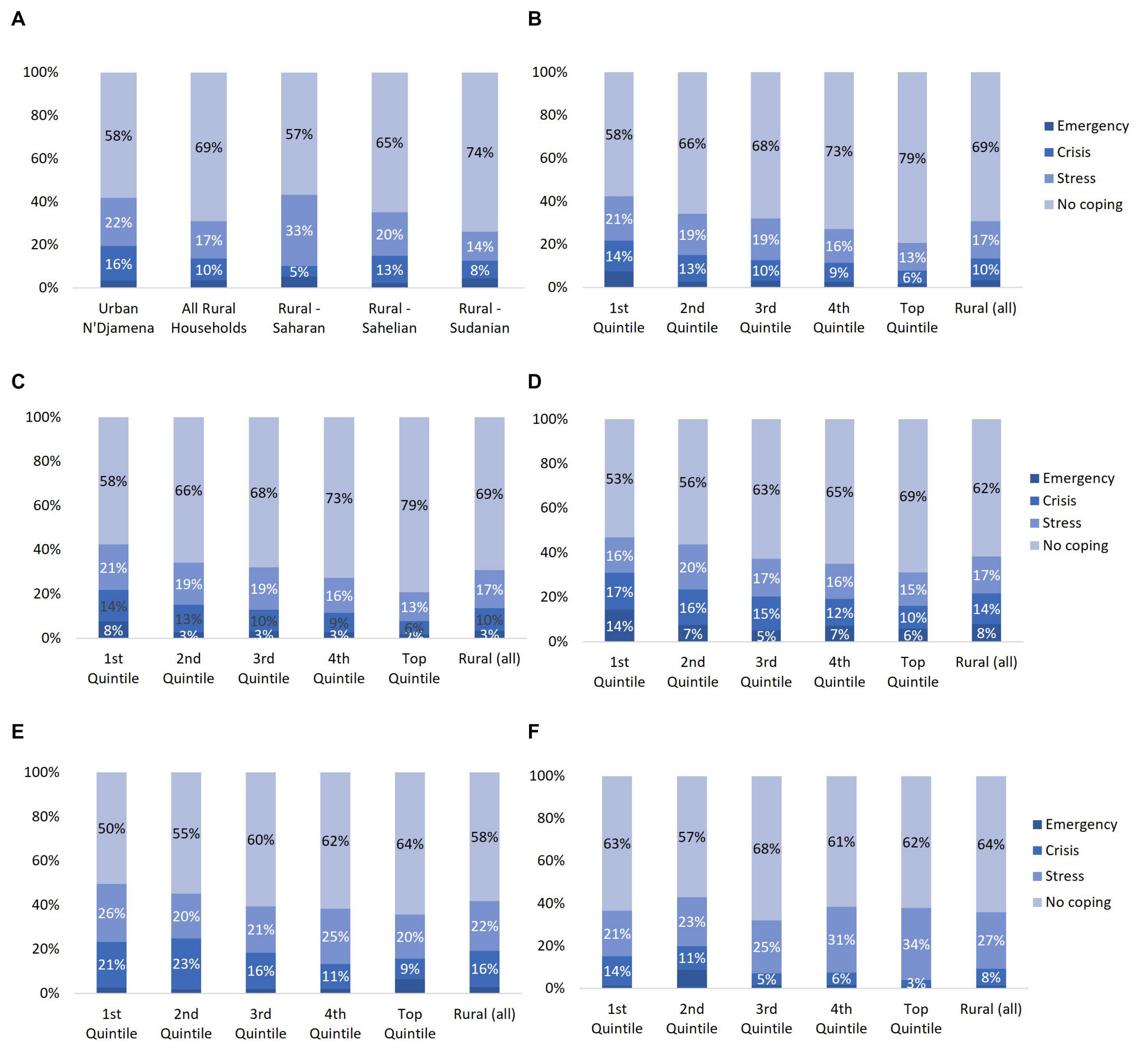


FIGURE 3
Livelihoods coping mechanism use by residence location and wealth quintile, 2020–2021. **(A)** By residence location in 2020; **(B)** by residence location in 2021; **(C)** by wealth quintile in rural 2020; **(D)** by wealth quintile in rural 2021; **(E)** by wealth quintile in N'Djamena 2020; **(F)** by wealth quintile in N'Djamena 2021.

urban areas. Characteristics associated with increased risk of adoption of crisis or emergency level coping mechanisms included large household size (OR = 1.87, CI: 1.36, 2.53), inefficient cooking methods (OR = 1.59, CI: 1.11, 2.27), poor housing materials (OR = 1.75, CI: 1.03, 2.97), and dependency on humanitarian aid as a primary income source as compared to agriculture (OR = 2.66, CI: 1.02, 6.92).

## 3.5. Association between COVID-19 income reduction and coping strategy use, household expenditures, and food consumption

In rural areas, the reported income reduction due to COVID-19 was associated with the use of stress (2020 OR = 1.33, CI: 1.02, 1.72; 2021 OR = 1.56, CI: 1.22, 1.99) and crisis (2020 OR = 1.60, CI: 1.11, 2.32; 2021 OR = 1.55, CI: 1.23, 1.96) but not emergency level coping mechanisms (Table 5). In 2020, rural households reporting COVID-19 income reduction were more likely to have poor food consumption than those that did not experience income reduction (OR = 1.35, CI: 1.00, 1.82) and COVID-19 income reduction was associated with lower short-term expenses (all $p = 0.047$) and long-term expenses (all $p < 0.01$) in both 2020 and 2021. A largely similar trend was observed in urban N'Djamena where households that reported COVID-19 income reductions were likely to use stress (2020 OR = 1.90, CI: 1.52, 2.38) and crisis (2020 OR = 1.46, CI: 1.10, 1.95; 2021 OR = 2.54, CI: 1.77, 3.66) coping mechanisms (emergency level coping mechanism were not examined due to small sample size). In 2020, households reporting income reduction had significantly lower short-term ($p < 0.01$), long-term ($p < 0.01$) and the proportion of foods expenditure (beta = 2.1%; $p = 0.01$) compared to households without

TABLE 3 Risk factors for reduced income due to COVID-19 in rural and urban areas of Chad, 2020–2021 (adjusted odds)*.

| | Rural households | | | | | | Urban households - N'Djamena | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | October 2020 (*n*=13,208) | | | October 2021 (*n*=14,730) | | | October 2020 (*n*=1,736) | | | October 2021 (*n*=2,231) | | |
| | AOR | (95%CI) | Value of *p* | AOR | (95%CI) | Value of *p* | AOR | (95% CI) | Value of *p* | AOR | (95%CI) | Value of *p* |
| Household demographic characteristics | | | | | | | | | | | | |
| Large size, 8+ members (Ref: ≤7 members) | | | | | | | 1.37 | (1.11, 1.70) | **<0.01** | | | |
| Household structure (Ref: Monogamous) | | | | | | | | | | | | |
| Polygamous household | | | | | | | 1.02 | (0.76, 1.37) | 0.88 | 1.27 | (0.99, 1.63) | 0.06 |
| Divorced/widowed/single household | | | | | | | **1.38** | **(1.05, 1.82)** | **0.02** | 1.15 | (0.88, 1.50) | 0.32 |
| Household head characteristics | | | | | | | | | | | | |
| Household head age (Ref: 25–34 years) | | | | | | | | | | | | |
| 15–24 years | 0.89 | (0.72, 1.10) | 0.28 | | | | | | | 0.51 | (0.27, 0.98) | 0.04 |
| 35–44 years | 1.04 | (0.89, 1.21) | 0.63 | | | | | | | 1.05 | (0.81, 1.38) | 0.71 |
| 45–54 years | 1.12 | (0.94, 1.33) | 0.19 | | | | | | | 1.14 | (0.86, 1.50) | 0.36 |
| ≥55 years | 0.99 | (0.81, 1.20) | 0.90 | | | | | | | 1.02 | (0.76, 1.37) | 0.90 |
| Female headed household (Ref: male) | **1.21** | **(1.04, 1.41)** | **0.01** | **1.29** | **(1.05, 1.58)** | **0.01** | | | | **1.27** | **(1.00, 1.62)** | **0.05** |
| Illiterate household head (Ref: Literate) | 0.87 | (0.74, 1.03) | 0.10 | **0.82** | **(0.68, 1.00)** | **0.05** | 1.18 | (0.94, 1.47) | 0.16 | **1.20** | **(0.99, 1.45)** | **0.07** |
| Disabled household head (Ref: not disabled) | | | | | | | | | | 1.26 | (0.94, 1.68) | 0.12 |
| Residence location and living conditions | | | | | | | | | | | | |
| Agroecological zone (Ref: Sudanian) | | | | | | | | | | | | |
| Sahelian zone | 1.54 | (0.99, 2.39) | 0.05 | | | | | | | | | |
| Saharan zone | **2.43** | **(1.04, 5.68)** | **0.04** | | | | | | | | | |
| No electric energy (Ref: electric) | 2.28 | (0.64, 8.15) | 0.20 | 3.91 | (1.98, 7.72) | <0.001 | **1.60** | **(1.27, 2.01)** | **<0.01** | **1.34** | **(1.11, 1.63)** | **<0.01** |
| Inefficient cooking method (Ref: efficient) | | | | | | | 1.00 | (0.76, 1.33) | 0.98 | | | |
| Poor housing material (Ref: brick/cement) | 1.22 | (0.93, 1.59) | 0.14 | | | | **0.51** | **(0.34, 0.75)** | **<0.01** | | | |
| Unimproved drinking water (Ref: improved) | | | | | | | | | | | | |
| Household income sources (Ref: agriculture) | | | | | | | | | | | | |
| Livestock[1] | **1.61** | **(1.16, 2.24)** | **0.01** | **1.37** | **(1.05, 1.80)** | **0.02** | – | – | – | – | – | – |

*(Continued)*

TABLE 3 (Continued)

| | Rural households | | | | | | Urban households - N'Djamena | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | October 2020 ($n$=13,208) | | | October 2021 ($n$=14,730) | | | October 2020 ($n$=1,736) | | | October 2021 ($n$=2,231) | | |
| Small trade | **1.47** | **(1.09, 1.98)** | **0.01** | 1.24 | (1.00, 1.55) | 0.05 | 1.19 | (0.76, 1.89) | 0.45 | 0.83 | (0.46, 1.48) | 0.52 |
| Skilled/unskilled/ artisanal labor$^2$ | **1.37** | **(1.03, 1.81)** | **0.03** | 1.08 | (0.82, 1.42) | 0.61 | **0.65** | **(0.43, 0.96)** | **0.03** | **0.49** | **(0.28, 0.84)** | **0.01** |
| Salaried work | – | – | – | – | – | – | 1.49 | (0.92, 2.42) | 0.11 | 0.85 | (0.48, 1.50) | 0.57 |
| Humanitarian Aid/Remittances | 1.29 | (0.84, 1.97) | 0.24 | 0.88 | (0.70, 1.12) | 0.31 | 0.93 | (0.45, 1.91) | 0.84 | 1.12 | (0.52, 2.42) | 0.78 |
| Others | 0.89 | (0.39, 2.03) | 0.78 | 1.13 | (0.76, 1.68) | 0.55 | **0.64** | **(0.37, 1.11)** | **0.11** | 0.74 | (0.38, 1.42) | 0.36 |

AOR, adjusted Odds Ratio. *Includes only covariates significant at $p < 0.10$ in univariate models; blank indicates covariate was not considered in adjusted model. $^1$For urban area, livestock as a primary income source was included to the agriculture group due to low proportion (0.9% in 2020 and 0.5% in 2021). $^2$For rural area, salaried work was included to the category of skilled/ unskilled/artisanal labor due to low proportions (1.8% in 2020 and 1.7% in 2021). Bold values present $p$-values <0.05.

income reduction; this association was not examined in 2021 due small sample size.

## 4. Discussion

Using 2 years of national ENSA survey data from Chad in 2020 and 2021, this study sought to characterize trends in household food security at the onset of the COVID-19 pandemic. Specifically, the analysis explored the risk factors for reported income loss due to COVID-19 and the use of crisis and emergency coping mechanisms and explored relationships between income loss, coping strategy use, food consumption, and household expenditures. In 2020, the reported income reduction was higher in urban areas than rural areas (65.9% vs. 61.1%) and in 2021, the trend in the income reduction was the opposite with a decrease in N'Djamena (to 57.6%) but an increase in rural areas (66.7%). Coping mechanism adoption trends were consistent with observed income reductions.

Among rural households, those headed by females, living in the Saharan zone, and engaged in livestock rearing, petty trade, or skilled/unskilled labor were at higher risk of income loss. In urban areas, households that were large and headed by individuals that were unmarried, female and/or illiterate were more likely to report income losses. However, the skilled/unskilled labor occupation was protective against income loss compared to those engaged in agriculture/livestock rearing in urban areas. There were many shared risk factors between coping mechanism adoption and COVID-19 related income reduction. Polygamous households, those with unmarried and female household heads, and households with agriculture as a main income source were at higher risk of adopting coping strategies in rural areas. In N'Djamena, polygamous families, those with illiterate household heads, and with poor living conditions were more likely to adopt severe coping mechanisms. Households that experienced COVID-19 income loss were more likely to use coping strategies, have lower short (preceding month)- and long-term (6 months) household expenses, and have poor or borderline food consumption, as compared to those with increased income or no change in income status.

### 4.1. Trends in COVID-19 related income reduction and use of livelihoods coping mechanism use

Two-thirds of households in both rural and urban areas reported COVID-19 income reductions, with greater reductions in urban areas in 2020 and rural areas in 2021. This finding is consistent with a multi-country study in Sub-Saharan Africa on COVID-19 impact that also reported two-thirds of households had COVID-19 related income losses with loss of family enterprise revenue and lost jobs being the most frequent causes (Dasgupta and Robinson, 2021). This is likely due to earlier and stricter enforcement of COVID-19 prevention measures in N'Djamena compared to rural areas. This observation in Chad reflects the global trend in the economic recessions in urban areas during 2020. A study on 2020 lockdowns in eight Asia pacific countries reported similar results, with a higher proportion of urban residents reporting a loss of jobs and reduced income since COVID-19 as compared to rural populations (Kang et al., 2021). It is not surprising that households with food production capacity would be more protected from the impacts of rising food prices, and COVID-19 related economic losses (FAO, 2020). Nevertheless, the prolonged nature of the pandemic and associated restrictions resulted in a progressive strain on livelihoods and a corresponding increase in the use of coping mechanisms between 2020 and 2021.

### 4.2. Risk factors for income loss and coping mechanism adoption

The identified risk factors for income loss and coping mechanisms adoption are related to socio-economically disadvantaged groups, including households with female-headed, illiterate, and unmarried heads. Households with these characteristics were already more likely to be economically disadvantaged—for example in rural households, 38% of the lowest wealth quintile were female headed households compared to 8% in the richest quintile and 83% of widowed/divorced/ single headed households were female headed. Single earner households and those with higher dependency ratios may

TABLE 4 Risk factors for crisis and emergency coping mechanism use in rural and urban areas of Chad, 2020–2021 (adjusted odds).

| | Rural households | | | | | | Urban households – N'Djamena | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | October 2020 (*n*=13,208) | | | October 2021 (*n*=14,730) | | | October 2021 (*n*=14,730) | | | October 2021 (*n*=2,231) | | |
| | AOR$^{*}$ | (95 CI) | Value of *p* | AOR$^{*}$ | (95 CI) | Value of *p* | AOR$^{*}$ | (95 CI) | Value of *p* | AOR$^{*}$ | (95 CI) | Value of *p* |
| Household demographic characteristics | | | | | | | | | | | | |
| Large size, 8+ members (Ref: ≤7 members) | | | | | | | 1.12 | (0.86, 1.46) | 0.41 | **1.87** | **(1.38, 2.53)** | **<0.01** |
| Households structure (Ref: monogamous) | | | | | | | | | | | | |
| Polygamous | | | | **1.18** | **(1.00, 1.38)** | **0.04** | **1.75** | **(1.27, 2.40)** | **<0.01** | 1.23 | (0.83, 1.82) | 0.31 |
| Divorced/ widowed/single | | | | **1.53** | **(1.19, 1.97)** | **0.00** | 1.05 | (0.76, 1.46) | 0.76 | 1.43 | (0.99, 2.06) | 0.06 |
| Household head characteristics | | | | | | | | | | | | |
| Household head age (Ref: 25–34 years) | | | | | | | | | | | | |
| 15–24 years | | | | 0.95 | (0.71, 1.27) | 0.73 | 0.90 | (0.38, 2.16) | 0.82 | | | |
| 35–44 years | | | | 1.03 | (0.88, 1.20) | 0.70 | 1.02 | (0.70, 1.48) | 0.93 | | | |
| 45–54 years | | | | 0.98 | (0.84, 1.13) | 0.75 | 1.19 | (0.80, 1.75) | 0.39 | | | |
| ≥55 years | | | | 1.14 | (0.96, 1.37) | 0.13 | 1.01 | (0.67, 1.51) | 0.97 | | | |
| Female headed household (Ref: male) | **1.78** | **(1.35, 2.35)** | **<0.01** | 1.30 | (0.99, 1.69) | 0.05 | | | | | | |
| Illiterate household head (Ref: Literate) | | | | | | | **1.33** | **(1.02, 1.72)** | **0.04** | | | |
| Disabled Household head (Ref: not disabled) | 1.26 | (0.90 1.76) | 0.18 | 1.24 | (0.98, 1.56) | 0.07 | | | | | | |
| Residence location and living conditions | | | | | | | | | | | | |
| Agroecological zone (Ref: Sudanian) | | | | | | | | | | | | |
| Sahelian zone | | | | | | | | | | | | |
| Saharan zone | | | | | | | | | | | | |
| No electric energy (Ref: electric) | | | | | | | **3.11** | **(0.94, 10.3)** | **0.06** | | | |
| Inefficient cooking method (Ref: efficient) | | | | | | | **1.45** | **(1.08, 1.93)** | **0.01** | **1.59** | **(1.11, 2.27)** | **0.01** |
| Poor housing material (Ref: brick/cement) | **2.10** | **(1.36, 3.21)** | **<0.01** | **0.73** | **(0.54, 0.99)** | **0.05** | 1.30 | (0.83, 2.04) | 0.26 | **1.75** | **(1.03, 2.97)** | **0.04** |
| Unimproved drinking water (Ref: Improved) | 1.27 | (0.95, 1.69) | 0.10 | | | | | | | | | |

*(Continued)*

TABLE 4 (Continued)

| | Rural households | | | | | | Urban households – N'Djamena | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | October 2020 (*n*=13,208) | | | October 2021 (*n*=14,730) | | | October 2021 (*n*=14,730) | | | October 2021 (*n*=2,231) | | |
| Household income sources (Ref: agriculture) | | | | | | | | | | | | |
| Livestock[1] | **0.58** | **(0.39, 0.85)** | **0.01** | 1.14 | (0.81, 1.61) | 0.45 | | | | | | |
| Petty trade | 0.65 | (0.41, 1.01) | 0.05 | 0.98 | (0.72, 1.34) | 0.89 | 0.72 | (0.46, 1.14) | 0.16 | 1.31 | (0.58, 2.96) | 0.52 |
| Skilled/unskilled/artisanal labor | **0.55** | **(0.39, 0.78)** | **<0.01** | 1.26 | (0.89, 1.78) | 0.19 | **0.53** | **(0.35, 0.79)** | **<0.01** | 0.71 | (0.33, 1.57) | 0.40 |
| Salaried work[2] | – | – | - | – | – | – | 0.76 | (0.47, 1.21) | 0.25 | 1.16 | (0.51, 2.60) | 0.73 |
| Humanitarian aid/Remittances | **0.55** | **(0.35, 0.87)** | **0.01** | 1.27 | (0.85, 1.91) | 0.24 | 0.86 | (0.41, 1.81) | 0.69 | **2.66** | **(1.02, 6.92)** | **0.04** |
| Others | **0.32** | **(0.15, 0.69)** | **<0.01** | **2.24** | **(1.37, 3.67)** | **<0.01** | 0.56 | (0.29, 1.06) | 0.08 | 0.70 | (0.25, 1.92) | 0.49 |

AOR, adjusted Odds Ratio. [1]For urban area, livestock as a primary income source was included to the agriculture group due to low proportion (0.9% in 2020 and 0.5% in 2021). [2]For rural area, salaried work was included to the category of Skilled/unskilled/artisanal labor due to low proportions (1.8% in 2020 and 1.7% in 2021). *Includes only covariates significant at $p < 0.10$ in univariate models; blank indicates covariate was not considered in model. Bold values present *p*-values <0.05.

be economically more vulnerable, and the patriarchal nature of society renders women and female headed households more vulnerable to economic losses due to more limited access to a broad spectrum of resources and opportunities.

In our study, the negative association between literacy and the economic impact could be linked to the fact that the main income source for illiterate household heads is subsistence agriculture, who were less likely to report income reductions due to COVID-19 as they retained access to their gardens/farms located close to the household. In this study, coping strategy index scores were the highest in urban areas in 2020. Studies that assessed determinants of coping mechanism adoption during COVID-19 lockdowns in other settings reported similar findings, with higher rates of coping mechanism use among urban residents and lower wealth groups during the early stages of the pandemic (Das et al., 2020). The high reduction in income due to COVID-19 and the subsequent increase in the use of emergency coping mechanisms is thus likely directly linked to the enforcement of COVID-19 prevention measures such as the prolonged border and market closures.

## 4.3. Geographic variations of rural food insecurity

When considering the three agro-ecological regions of Chad, households in the Sudanian zone were wealthier, with ~32% of the richest quintile residing in the area, and agriculture was a more common income source, which likely contributed to households having more food stocks and/or agriculture-based income sources that suffered fewer COVID-19 related disruptions. The Saharan zone, which accounts for only ~6% of the rural population, was less wealthy, with more than half of households in the lowest quintile, and the population engaged primarily in livestock rearing (30%) and (un) skilled paid labor or salaried jobs (28%), both of which posed a greater risk of COVID-19 economic losses as compared to agriculture. In Chad, cross-border livestock trade is a major way transhumant and agro-pastoral households earn a living in the Saharan zone, mediated through weekly livestock markets in a complex relationship between ethnic groupings of herders, traders and other intermediaries (Koussou, 2002). Lockdowns and movement restrictions resulted in disruptions of livestock production and supply chains, declines in livestock sales due to market closure, causing the pastoralists to lose income (Griffith et al., 2021). In adjusted models that account for these factors, households in the Saharan zone were twice (AOR = 2.03, CI: 1.04, 5.68) as likely as those in the Sudanian zone to report COVID-19 income loses in 2020, but they were not at increased risk for income loss in 2021 or coping strategy adoption in either year. The population in the Sahelian zone followed the same pattern of increased risk for COVID-19 related income loss in 2020 only (AOR = 1.54, CI: 0.99, 2.39) and had similar coping mechanism use. One potential contributing factor for income losses in the Sahel was the poor rainy seasons leading into the pandemic which led to fodder deficits among pastoralists (ECOWAS – SWAC/OECD initiative, 2008; World Bank, 2020).

## 4.4. The COVID-19 response

Social safety net programs were rolled out rapidly in Chad in response to the pandemic, with about 20% of households receiving at least one government transfer; additionally, 437,000 food kits were distributed to vulnerable households and agricultural inputs (seeds, equipment) were provided to smallholder farmers (World Bank, 2022b). Cash safety net programs have become an effective strategy (Makkar et al., 2022), as compared to in-kind food provision, to reduce food insecurity and in Chad, cash transfers have shown to be effective among vulnerable groups such as female headed households and those with low educational attainment and incomes (Dasgupta and Robinson, 2022). While cash transfers can be rapidly scalable, one notable disadvantage in their application by governments

**TABLE 5** Association between COVID-19 income reduction and coping strategy use, food consumption and food expenditure.

| | Rural households | | | | | |
|---|---|---|---|---|---|---|
| | October 2020 ($n$ =13,208) | | | October 2021 ($n$ =14,730) | | |
| | AOR$^4$ | (95 CI) | Value of $p$ | AOR$^4$ | (95 CI) | Value of $p$ |
| Association between reported income reduction due to COVID-19 and coping strategy use$^1$ | | | | | | |
| Stress coping mechanism use (Ref: no) | **1.33** | **(1.02, 1.72)** | **0.04** | **1.56** | **(1.22, 1.99)** | **<0.01** |
| Sell non-productive goods (Ref: no) | 1.45 | (0.86, 2.45) | 0.16 | 1.34 | (0.86, 2.09) | 0.19 |
| Buy/borrow food on credit (Ref: no) | **1.41** | **(1.03, 1.94)** | **0.03** | **1.77** | **(1.31, 2.39)** | **<0.01** |
| Spend savings (Ref: no) | **1.43** | **(0.99,2.06)** | **0.05** | 1.36 | (0.84, 2.19) | 0.21 |
| Sell livestock (Ref: no) | **1.26** | **(0.93, 1.69)** | **0.14** | **1.53** | **(1.08, 2.17)** | **0.02** |
| Crises coping mechanisms use (Ref: no) | **1.60** | **(1.11, 2.32)** | **0.01** | 1.55 | (1.23, 1.96) | **<0.01** |
| Harvesting immature crops (Ref: no) | **2.69** | **(1.59, 4.57)** | **<0.01** | **1.62** | **(1.23, 2.15)** | **0.00** |
| Remove the children from school (Ref: no) | 1.14 | (0.84, 1.55) | 0.38 | **1.73** | **(1.17, 2.56)** | **0.01** |
| Reducing health or education spending (Ref: no) | 1.09 | (0.55, 2.17) | 0.81 | 1.23 | (0.81, 1.86) | 0.33 |
| Emergency coping mechanisms use (Ref: no) | 1.30 | (0.90, 1.89) | 0.16 | 1.23 | (0.91, 1.65) | 0.18 |
| Send household members for begging (Ref: no) | **2.65** | **(1.24, 5.63)** | **0.01** | 0.93 | (0.57, 1.52) | 0.77 |
| Selling parcels of land (Ref: no) | 1.36 | (0.78, 2.36) | 0.27 | **1.53** | **(1.02, 2.29)** | **0.04** |
| Selling the latest breeding livestock (Ref: no) | 1.14 | (0.75, 1.76) | 0.53 | **1.61** | **(1.11, 2.34)** | **0.01** |
| Association between reported income reduction due to COVID-19 and food consumption$^1$ | | | | | | |
| Poor/borderline consumption (Ref: acceptable) | **1.44** | **(1.04, 2.00)** | **0.03** | 1.32 | (0.99, 1.74) | 0.05 |
| Association between reported income reduction due to COVID-19 and food expenditures$^2$ | | | | | | |
| | Adjusted $\beta$ | (95 CI) | Value of $p$ | Adjusted $\beta$ | (95 CI) | Value of $p$ |
| Short term expenses (preceding month)$^3$ | **−0.09** | **(−0.16, −0.01)** | **0.05** | **−0.17** | **(−0.28, −0.06)** | **0.00** |
| Long term expenses (6 months)$^3$ | **−0.12** | **(−0.22, −0.02)** | **0.02** | **−0.15** | **(−0.27, −0.02)** | **0.03** |
| Food expenditure proportion, % | 0.60 | (−0.81, 2.01) | 0.40 | 0.89 | (−1.06, 2.84) | 0.36 |
| | Urban households – N'Djamena | | | | | |
| | October 2020 ($n$ = 1,736) | | | October 2021 ($n$ = 2,231) | | |
| | Adjusted odds | (95 CI) | Value of $p$ | Adjusted odds | (95 CI) | Value of $p$ |

*(Continued)*

TABLE 5 (Continued)

| | Rural households | | | | | |
|---|---|---|---|---|---|---|
| | October 2020 (*n* =13,208) | | | October 2021 (*n* =14,730) | | |
| | AOR[4] | (95 CI) | Value of *p* | AOR[4] | (95 CI) | Value of *p* |
| Association between reported income reduction due to COVID-19 and coping strategy use[1] | | | | | | |
| Stress coping mechanism use (Ref: no) | **1.90** | **(1.52, 2.38)** | **<0.01** | 1.04 | (0.86, 1.25) | 0.71 |
| Sell non-productive goods (Ref: no) | **2.01** | **(1.40, 2.88)** | **<0.01** | **0.60** | **(0.45, 0.81)** | **0.01** |
| Buy/borrow food on credit (Ref: no) | **1.72** | **(1.28, 2.31)** | **<0.01** | 1.28 | (0.41, 3.96) | 0.67 |
| Spend savings (Ref: no) | **1.42** | **(0.98, 2.06)** | **0.07** | 0.76 | (0.52, 1.13) | 0.18 |
| Sell livestock (Ref: no) | **1.82** | **(0.89, 3.73)** | **0.10** | 1.02 | (0.79, 1.32) | 0.86 |
| Crises coping mechanisms use (Ref: no) | **1.46** | **(1.10, 1.95)** | **0.01** | **2.54** | **(1.77, 3.66)** | **<0.01** |
| Harvesting immature crops (Ref: no) | | | | **2.23** | **(1.39, 3.58)** | **<0.01** |
| Remove the children from school (Ref: no) | **1.37** | **(0.98, 1.92)** | **0.06** | 1.36 | (0.67, 2.75) | 0.40 |
| Reducing health or education spending (Ref: no) | 0.66 | (0.34, 1.28) | 0.22 | **2.04** | **(0.97, 4.31)** | **0.06** |
| Emergency coping mechanisms use (Ref: no) | 1.03 | (0.56, 1.89) | 0.92 | 1.37 | (0.65, 2.92) | 0.41 |
| Send household members for begging (Ref: no) | 1.18 | (0.37, 3.74) | 0.78 | 0.59 | (0.22, 1.57) | 0.29 |
| Selling parcels of land (Ref: no) | 0.73 | (0.33,1.63) | 0.44 | 0.23 | (0.01, 9.96) | 0.45 |
| Selling the latest breeding livestock (Ref: no) | 0.58 | (0.18,1.87) | 0.36 | 2.64 | (0.31, 22.5) | 0.37 |
| Association between reported income reduction due to COVID-19 and food consumption[1] | | | | | | |
| Poor/borderline consumption (Ref: acceptable) | 0.86 | (0.63, 1.19) | 0.37 | 1.11 | (0.78, 1.58) | 0.57 |
| Association between reported income reduction due to COVID-19 and household expenditures[2] | | | | | | |
| | Adjusted *β* | (95 CI) | Value of *p* | | | |
| Short term expenses (preceding month)[3] | **−0.15** | **(−0.22, −0.07)** | **<0.01** | Not estimated due to small sample size (<100) | | |
| Long term expenses (6 months)[3] | **−0.39** | **(−0.49, −0.28)** | **<0.01** | | | |
| Food expenditure proportion, % | **2.07** | **(0.44, 3.70)** | **0.01** | | | |

[1] AOR, adjusted Odds Ratio for dichotomous variable. [2] Linear regression was used for food expenditure (monthly expenses, long-term expenses, and food expenditure proportion) as continuous variables. [3] Log transformed. [4] Adjusted linear or logistic regression models were used, accounting for agro-ecological zone, household head's sex, age, marital status, literacy, occupation, household composition (i.e., size, disability, and chronic disease status of family members) and living conditions (i.e., dwelling type, water, energy, and cooking source). Bold values present *p*-values <0.05.

in the early COVID-19 response was the risk of excluding the most vulnerable groups, such as informal workers and those without access to social insurance. Temporary assistance and humanitarian relief programming, which were intended to address this gap, were slower to be established and faced both corruption and targeting challenges (Devereux et al., 2020). Social safety net programs do appear to have reduced extreme food insecurity (the probability of going without food for a whole day) in Chad (Dasgupta and Robinson, 2021). In November 2021, WFP's impact monitoring of its COVID-19 response in the provinces of Logone Occidental and Logone Oriental showed that the proportion of households reporting acceptable food consumption increased from 43 to 70% while the use of crisis or emergency coping strategies reduced from 26 to 16% among those assisted (Unpublished).

## 4.5. Implications for future responses

Findings of this study suggest that targeting female and unmarried household heads, and in the case of economic shocks, urban households may be most impactful. Notable regional differences in rural food security could also inform targeting strategies at the national level. However, while this is in line with the common understanding of vulnerability and targeting, the study also reveals some counter-intuitive aspects that future responses may need to consider. Dependence on agriculture and illiteracy of the household head are not necessarily synonymous with high vulnerability. Thus, the targeting of responses needs to be tailored to the evolution of the shock in question and how this affects different sub-groups of the population. Furthermore, the study reveals a differential impact of households dependent on skilled/unskilled/artisanal labor which was a risk factor to income loss in the rural setting but a protective factor in the urban setting. This suggests the need for a local, systemic understanding of household economic activities and how these are affected by the evolution of the shock. Alarcon et al. (2021) emphasize the need for a food systems approach in the context of health emergencies and caution on common failures such as the lack of differentiation of people working in the food systems and how they are organized among others (Alarcon, Dominguez-Salas, Fèvre, & Rushton, 2021).

## 4.6. Limitations

This analysis leveraged nationally representative datasets with relatively large sample sizes to characterize the economic impact of COVID-19 between 2020 and 2021 in both rural and urban areas. Due to the nature of secondary analysis of existing survey data, the study had several critical limitations. First, rural and urban surveys were conducted independently, though at similar time points in the year, with different sampling frames necessitating separate analyses. The surveys applied the same population-based sampling methodology in each year, however, samples were independent and change over time in specific households could not be examined. Second, the primary outcome—COVID-19 income reduction—is self-reported by the respondent, and subject to both recall and reporting bias. A third limitation is that the ENSA data set did not include income amounts, but rather asked how income had changed due to COVID-19 (i.e., a categorical variable) which limited the depth of analysis possible, where quantifying income losses would have been preferable. While the question focused on COVID-19 income-related losses, the survey did not specifically query for other factors that may have contributed to income reductions such as poor rainfall which affected crop production and harvest in some areas of the country in 2020. A final limitation is that the study was unable to characterize the impact of the social safety net and humanitarian response on COVID-19 impacts.

## 5. Conclusion

The COVID-19 pandemic caused a significant increase in household food insecurity in both rural and urban areas in Chad. Two-thirds of households lost income due to COVID-19 in 2020 and 2021; during early COVID in 2020, a larger proportion of urban households reported income loss, whereas later in 2021, a larger proportion of rural households reported COVID-19 related income reductions. In 2020, higher levels of income loss in N'Djamena were accompanied by higher adoption rates of emergency and crisis level coping mechanisms. However, as the pandemic progressed, impacts on urban households subsided while an opposite trend was observed for rural households which saw greater income losses and coping mechanism adoption. Rural households in the Saharan zone were most likely to report COVID-19 related income losses and had the highest rates of coping mechanism use in both 2020 and 2021. Socio-economically disadvantaged groups, including those with less wealth and households headed by females, illiterate and unmarried heads had increased risk of income loss and coping mechanism adoption, which is consistent with findings from other studies in the region.

This study elucidates the potential impact pathways of COVID-19 from a household economic downturn to limited food spending, poor food consumption, and increased use of short-term coping mechanisms. While large-scale lockdowns seen in the early COVID-19 response are unlikely to reoccur, the differential impact of these measures on urban and rural populations and by household income source was notable. In the case of the COVID-19 pandemic lockdowns, it is apparent that vulnerable households in both rural and urban areas of Chad were more likely to be impacted, however, the difference between wealth quintiles was modest, with larger variations seen by geographic location. This observation suggests that responses to future economic shocks should incorporate an in-depth regional analysis to inform more refined targeting strategies. Given that larger households, those with poor living conditions, and those with unmarried, female or illiterate household heads faced increased risk for income loss and emergency or crisis-level coping mechanism adoption and that these are often criteria for targeting assistance, results from this study suggest that typical beneficiary selection strategies were likely to be appropriate in the COVID-19 response.

The variation in impact on households according to livelihood groups and rural and urban settings suggests the need for proactive, local food-systems based solutions, that address vulnerabilities of specific sub-groups but also reinforce livelihood opportunities and increase resilience. One notable challenge when considering responses to large scale economic shocks going forward is the coordination of social safety net programs and humanitarian response, and perhaps importantly, the provision of rapid assistance to these groups, which may not be included in more rapidly scalable social safety net programs.

## Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the data that support the findings of this study are available from World Food Programme Chad. Data are available with the permission of World Food Programme Chad. Requests to access these datasets should be directed to edgar.wabyona@wfp.org.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

YK, EW, and SD contributed to conception and design of the study. EW organized the database. YK performed the statistical analysis. YK and SD wrote the first draft of the manuscript. EW, FU, and AT wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

## Funding

This study was funded by World Food Programme Chad.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## References

Alarcon, P., Dominguez-Salas, P., Fèvre, E. M., and Rushton, J. (2021). The importance of a food systems approach to low and middle income countries and emerging economies: a review of theories and its relevance for disease control and malnutrition. *Front. Sustain. Food Syst.* 5:642635. doi: 10.3389/fsufs.2021.642635

Arndt, C., Davies, R., Gabriel, S., Harris, L., Makrelov, K., Robinson, S., et al. (2020). COVID-19 lockdowns, income distribution, and food security: an analysis for South Africa. *Glob. Food Sec.* 26:100410. doi: 10.1016/j.gfs.2020.100410

Béné, C., Bakker, D., Rodriguez, M. C., Even, B., Melo, J., and Sonneveld, A. (2021). Impacts of COVID-19 on people's food security: Foundations for a more resilient food system. Executive summary. Executive Summary February 2021. CGIAR COVID-19 Hub. doi: 10.2499/p15738coll2.134298

Buheji, M., da Costa Cunha, K., Beka, G., and Mavrić, B. (2020). The extent of COVID-19 pandemic socio-economic impact on global poverty. A global integrative multidisciplinary review. *Am. J. Econ.* 10, 213–224. doi: 10.5923/j.economics.20201004.02

Burström, B., and Tao, W. (2020). Social determinants of health and inequalities in COVID-19. *Eur. J. Pub. Health* 30, 617–618. doi: 10.1093/eurpub/ckaa095

Chirisa, I., Mutambisi, T., Chivenge, M., Mabaso, E., Matamanda, A. R., and Ncube, R. (2022). The urban penalty of COVID-19 lockdowns across the globe: manifestations and lessons for anglophone sub-Saharan Africa. *GeoJournal* 87, 815–828. doi: 10.1007/s10708-020-10281-6

Das, S., Rasul, M. G., Hossain, M. S., Khan, A. R., Alam, M. A., Ahmed, T., et al. (2020). Acute food insecurity and short-term coping strategies of urban and rural households of Bangladesh during the lockdown period of COVID-19 pandemic of 2020: report of a cross-sectional survey. *BMJ Open* 10:e043365. doi: 10.1136/bmjopen-2020-043365

Dasgupta, S., and Robinson, E. J. Z. (2021). Food insecurity, safety nets, and coping strategies during the COVID-19 pandemic: multi-country evidence from sub-Saharan Africa. *Int. J. Environ. Res. Public Health* 18:9997. doi: 10.3390/ijerph18199997

Dasgupta, S., and Robinson, E. J. Z. (2022). Impact of COVID-19 on food insecurity using multiple waves of high frequency household surveys. *Sci. Rep.* 12:1865. doi: 10.1038/s41598-022-05664-3

Devereux, S., Béné, C., and Hoddinott, J. (2020). Conceptualising COVID-19's impacts on household food security. *Food Secur* 12, 769–772. doi: 10.1007/s12571-020-01085-0

ECOWAS – SWAC/OECD initiative. (2008). *Livestock and regional market in the Sahel and West Africa potentials and challenges*. Paris:Sahel and West Africa Club/OECD.

FAO. (2020). *Revised humanitarian response (may–December 2020): Coronavirus disease 2019 (COVID-19); technical report*. FAO: Rome, Italy.

FAO, IFAD, UNICEF, WFP, and WHO. (2022). *The state of food security and nutrition in the world 2022: repurposing food and agricultural policies to make healthy diets more affordable*.

Griffith, E., Craige, S., Manzano, P., Pius, L., and Jost, C. (2021). Chapter eight - impacts of the COVID-19 pandemic on food security among east and west African pastoralists. *Adv Food Secur Sustain* 6, 231–261. doi: 10.1016/bs.af2s.2021.07.004

International Labor Organization (2021). *ILO monitor: COVID-19 and the world of work. Seventh edition updated estimates and analysis*. Geneva, Switzerland:International Labor Organization.

Kang, Y., Baidya, A., Aaron, A., Wang, J., Chan, C., and Wetzler, E. (2021). Differences in the early impact of COVID-19 on food security and livelihoods in rural and urban areas in the Asia Pacific region. *Glob. Food Sec.* 31:100580. doi: 10.1016/j.gfs.2021.100580

Koussou, M. (2002). *Diagnostic et propositions en vue de moderniser le commerce et la transformation des produits de l'elevage au TCHAD: rapport de mission d'appui au PASEP. République du Tchad Ministère de l'élevage Direction -générale Coordination du PASEP*. Yaoundé: Ministère de l'Elevage, 61 p.

Macharia, P. M., Joseph, N. K., Sartorius, B., Snow, R. W., and Okiro, E. A. (2021). Subnational estimates of factors associated with under-five mortality in Kenya: a spatio-temporal analysis, 1993-2014. *BMJ Glob. Health* 6:e004544. doi: 10.1136/bmjgh-2020-004544

Makkar, S., Manivannan, J. R., Swaminathan, S., Travasso, S. M., John, A. T., Webb, P., et al. (2022). Role of cash transfers in mitigating food insecurity in India during the COVID-19 pandemic: a longitudinal study in the Bihar state. *BMJ Open* 12:e060624. doi: 10.1136/bmjopen-2021-060624

Mennechet, F. J. D., and Dzomo, G. R. T. (2020). Coping with COVID-19 in sub-Saharan Africa: what might the future hold? *Virol. Sin.* 35, 875–884. doi: 10.1007/s12250-020-00279-2

Negesse, A., Woyraw, W., Temesgen, H., Teka, Y., Yismaw, L., Akalu, T. Y., et al. (2022). Spatial exploration of non-resilience to food insecurity, its association with COVID-19 and household coping strategies in east Gojjam districts, Northwest Ethiopia, 2020. *Sci. Rep.* 12:15511. doi: 10.1038/s41598-022-19963-2

Padmaja, R., Nedumaran, S., Jyosthnaa, P., Kavitha, K., Abu Hatab, A., and Lagerkvist, C. J. (2022). COVID-19 impact on household food security in urban and peri-urban areas of Hyderabad. *India Front Public Health* 10:814112. doi: 10.3389/fpubh.2022.814112

Patel, V., Chisholm, D., Dua, T., Laxminarayan, R., and Medina-Mora, M. E. (2015). *Mental, neurological, and substance use disorders: disease control priorities, third edition (volume 4)*. Washington, DC: World Bank.

Shahidul, M., and Mostafa, I. (2021). Coping strategies of low-income households in Bangladesh during the COVID-19 pandemic. *J Bangladesh Stud* 23, 56–78.

Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD (2020). Enquête nationale de sécurité alimentaire (ENSA) 2020. Tchad. (Données collectées en février–mars 2021). Available at: https://sisaaptchad.org/wp-content/uploads/2021/09/Rapport-ENSA-fevrier-2021-vf.pdf

Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD (2022). Enquête Nationale de Sécurité Alimentaire au TCHAD (ENSA) RAPPORT (Données collectées en février 2022). N'Djaména, SISAAP.

Tchana Tchana, F., Kassim, O., Savadogo, A., Ouedraogo, A., and Coulibaly, M. (2022). *Chad economic and poverty update under COVID-19, spring 2020* World Bank, Washington, DC:

WFP VAM resource center. (2021). Livelihood Coping Strategies – Food Security. *WFP, Rome*. Available at: https://resources.vam.wfp.org/data-analysis/quantitative/food-security/livelihood-coping-strategies-food-security

WHO. (2023). WHO Health Emergency Dashboard. WHO (COVID-19) Homepage. Available at: https://covid19.who.int/region/afro/country/td

Wiesmann, D., Bassett, L., Benson, T., and Hoddinott, J. (2009). *Validation of the world food programme's food consumption score and alternative indicators of household food security*. Washington, DC: INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE.

Workie, E., Mackolil, J., Nyika, J., and Ramadas, S. (2020). Deciphering the impact of COVID-19 pandemic on food security, agriculture, and livelihoods: a review of the evidence from developing countries. *Curr Res Environ Sustain* 2:100014. doi: 10.1016/j.crsust.2020.100014

World Bank. (2020). Where climate change is reality: Supporting Africa's Sahel pastoralists to secure a resilient future. Washington, DC:World Bank. Available at: worldbank.org.

World Bank. (2022a). *Chad overview: development news, research, data*. Washington, DC:World Bank.

World Bank. (2022b). *Food security update (update November 10, 2022)*. Washington, DC:World Bank.

TYPE Original Research
PUBLISHED 01 June 2023
DOI 10.3389/fsufs.2023.1143595

OPEN ACCESS

EDITED BY
Subhasis Mandal,
Central Soil Salinity Research Institute (ICAR), India

REVIEWED BY
Feroze Sheikh,
Central Agricultural University, India
Kiran Kumar TM,
National Institute for Agricultural Economics and Policy Research (NIAP), India

*CORRESPONDENCE
Linna Li
✉ lnli@ckgsb.edu.cn

RECEIVED 13 January 2023
ACCEPTED 02 May 2023
PUBLISHED 01 June 2023

CITATION
Xie L, Zhang J, Huang W, Ke D and Li L (2023) Relationship between rural land titling and land transfer in China: a systematic literature review and meta-analysis.
*Front. Sustain. Food Syst.* 7:1143595.
doi: 10.3389/fsufs.2023.1143595

# Relationship between rural land titling and land transfer in China: a systematic literature review and meta-analysis

Lin Xie[1], Juan Zhang[1], Wenyi Huang[1], Doudou Ke[1] and Linna Li[2]*

[1]College of Economics and Management, South China Agricultural University, Guangzhou, China, [2]School of Economics, Central University of Finance and Economics, Beijing, China

The traditional land system of rural communities in China has been an obstacle to the sustainable development of land transfer. To facilitate a more efficient allocation of resources, the Chinese government has implemented the largest rural land titling action in the world. However, there has been much debate in scholarly circles regarding the correlation between rural land titling and rural land transactions. By employing meta-analysis technology, this paper evaluates the relationship between rural land titling and rural land transactions. According to the meta-analysis results, rural land titling is only a minor contributor to rural land transfer; it only contributes to rural land transfer-out, with no effect on rural land transfer-in. Furthermore, education, age, labor force, agricultural fixed assets owned, area of contracted rural land, and publication time were identified as situational variables that affect the relationship between rural land titling and rural land transfer-out. This research provides insight into how to promote the sustainable development of agricultural land economy by promoting land transfer, as well as further topics for future study.

KEYWORDS

**rural land titling, land transfer, China, meta-analysis, sustainable development**

## Introduction

Agricultural production in China is dominated by smallholder farms because of the Household Contract Responsibility System (HCRS), which allocates the use rights of collectively owned farmland to rural households based on long-term contracts between households and local village collectives (Ye, 2015). Under the HCRS, members of the community collective have the right to acquire the right to contract land, resulting in China becoming a country dominated by small farmers. Data from China's Third Agricultural Census show that the number of small farmers nationwide accounts for more than 98% of agricultural operators, and the area of small farmers accounts for 70% of the total cultivated land. There are 230 million households in China's current farmers, with an average operating scale of 0.52 hectares and 210 million households operating <0.67 hectares (Xinhua News Agency, 2019). The excessively small scale of operations in China's agricultural sector has hindered the application of modern agricultural technologies, and therefore, through land transfer to expand the scale of individual operators, it is helpful to reduce production costs (Xu et al., 2011); The land transfer also has promoted agricultural intensive, industrialization and standardization, as well as the improvement of production efficiency (Zhang, 2010). Therefore, as early as 1984, the Chinese government put forward the idea of encouraging the gradual concentration of land to those who are capable of farming, and taking the path of large-scale operations. Subsequently, the concept of land transfer emerged. Land transfer denotes the process through which farmers exchange their rural land use rights, enabling those who seek to enlarge their agricultural scope to lease the rural land held by others. Land transfer-in pertains to farmers who desire to augment their agricultural scale by renting rural land from fellow farmers, whereas land transfer-out refers to farmers who lease out their own rural land holdings (Gao et al., 2020). By 2014, the State Council of China issued the "Opinions on Guiding the Orderly Transfer and Development of Rural Land Use Rights for Moderately-sized Agricultural Operations", requiring all levels of government to guide the orderly transfer of land use rights to expand the scale of agricultural operations (Xinhua News Agency, 2014).

However, as a country in transition, China has long adhered to the collective rural land ownership, with rural land owned by village collectives. Farmers have contract rights but village collectives retain the right to adjust land allocations (Zhang and Donaldson, 2013). This special property structure leads to unclear ownership of agricultural land in China and numerous rural land-related disputes, which hinders rural land transfer transactions and optimal rural land allocation (Bu and Liao, 2022). Under the influence of urbanization, there has been a rapid decrease in China's rural population as it migrates to urban areas. Additionally, under China's existing rural land system, land ownership is held by the collective of peasant communities, with the peasants merely contracted to use the land for production. As a result, ownership disputes often arise during the process of land transfer (Xie and Luo, 2013). The land system that restricts transactions leads to land abandonment and inefficient use, which determines the sustainable development of rural China (Li et al., 2018; Wang et al., 2018; Guo et al., 2019). In 2009–2018, China completed the world's largest rural land titling action at a cost of RMB60 billion. Land titling refers to the process wherein each rural household enters into a written agreement with the collective entity possessing the land, subsequently obtaining a land certificate. This certificate delineates the specific land parcel, its boundaries, and the encompassing area, with the intent of formalizing pre-existing land contracts and land use rights. Furthermore, it permits the utilization of land use rights as collateral (Cheng et al., 2019). Secure the collective and non-exclusive land rights of multiple types of land to individual farmers in an exclusive manner. Through the process of titling, the right of long-term use and transfer of land was granted to the farmers (Yan, 2010). The action clarified farmers' contract and management rights over rural land and prohibited further adjustments, greatly enhancing farmers' rural land property rights (Zhang L. et al., 2020).

In general, as indicated by Figure 1. The collective ownership of agricultural land in China has resulted in an equitable distribution of land per household. However, the country's vast population has led to a pattern of small-scale farming, wherein each household can only manage a diminutive plot of farmland. This practice has hindered the adoption of modern agricultural technologies, thereby limiting agricultural productivity. To address this issue, the Chinese government and researchers have advocated for enlarging the scale of individual households through the transfer of rural land. Nevertheless, the collective ownership of rural land poses significant legal and practical challenges to the transfer of land. To overcome these challenges, the Chinese government has implemented a land titling effort that grants farmers the right to freely transfer land. This policy weakens the rights of rural communities over the land, but it is necessary to facilitate the transfer of rural land and enhance overall agricultural productivity.

A clear definition of property rights is an important prerequisite for transactions and optimally allocated resources (Coase, 1960). Studies from various countries have shown that clear definitions of property rights promote rural land transfer by reducing transaction asymmetry, improving the perception of property rights security, and increasing credit availability for farmers (Carter and Olinto, 2003; Boucher et al., 2005; Gould et al., 2006; Holden et al., 2007; Chamberlin and Ricker-Gilbert, 2016). Some studies from China suggest that China's rural land titling action has contributed to rural land transfer (Ma et al., 2015; Cheng et al., 2016, 2019; Liu et al., 2017; Xu et al., 2017; Ye et al., 2018; Wang, 2019).

Conversely, some argue that China's land titling action hinders rural land transfer. That argument is based on the special importance of land in Chinese culture (Fei, 1998) as the personified property of farmers. Farmers' special feelings toward the farmland are further bolstered by land titling (Luo, 2019). The endowment effect is the tendency for people who own a good to value it more than people who do not (Knetsch, 1989; Kahneman et al., 1990; Morewedge and Giblin, 2015). In this case, farmers show an endowment effect when transferring rural land, that is, willingness to accept is higher than willingness to pay, which ultimately hinders rural land transfer (Zhong, 2013; Luo, 2017). This view is also supported by empirical studies (Fu et al., 2016; Cai and Xia, 2017; Lin et al., 2017).

The endowment effect has shown that the transaction of property rights for rural land is not as simple as Coase's analytical framework suggests. At the same time, the process of land titling and registration involves more complex interactions with rural communities. For example, research indicates that land titling can alter farmers' interest goals and thus affect mutual aid mechanisms in village society (Hong and Luo, 2023). Consequently, behind land titling lies not only farmers' economic calculations, but also some social issues. For instance, in the context of land titling, the number of lawsuits related to rural land property rights has not decreased, but has increased annually (Sun, 2021). Therefore, the relationship between land titling and land transfer should not only be analyzed from an efficiency perspective, but also from the perspective of equity during the titling process and afterwards (Feng et al., 2020). These factors may obfuscate the relationship between land titling and land transfer.

The foregoing implies that existing studies on the relationship between China's rural land titling and rural land transfer are ambiguous. On the one hand, this is partly because of existing studies that have referred to rural land transfer-in and transfer-out as "transfer", whereas farmers might have inconsistent behavior patterns when carrying out rural land transfer-in and transfer-out. Studies have demonstrated that land transfer-in behavior is mainly observed among farmers with higher initial income levels and better economic conditions, whereas land transfer-out behavior is mainly observed among farmers with lower initial income levels and poorer economic conditions. Moreover, land transfer-in has increased farmers' income, while land transfer-out has decreased

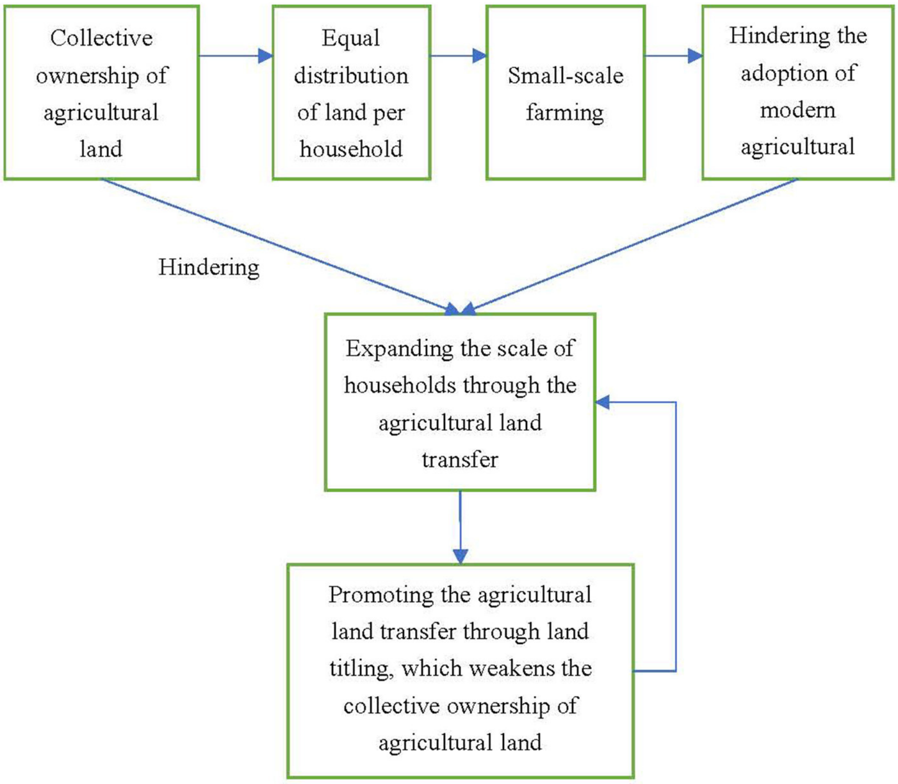


FIGURE 1
The relationship between collective ownership of agricultural land and land transfer.

farmers' income, thereby widening the income gap among rural residents in China (Du and Zhang, 2022). On the other hand, there is a moderator variable in the relationship between the variables used in different studies (Hunter and Schmidt, 2004). Most study sample data in the existing literature are limited to a certain region, so study results often apply only to a specific region. China's vast territory and wide regional disparities have led to heterogeneity of previous studies on rural areas in different regions and contexts, greatly weakening the universality of study conclusions (Xie et al., 2020). To this end, two questions remain to be clarified: (1) Has China's rural land titling action really contributed to rural land transfer? (2) What situational factors influence the relationship between the two?

As a comprehensive effect size assessment method, meta-analysis method has been widely applied in agricultural economics (Baumgart-Getz et al., 2012). As a quantitative method, meta-analysis and its derivative, meta-regression analysis method, not only assess the type and strength of the relationship between variables but also explore the moderator variable in that relationship (Miller and Toulouse, 1986). If the relationship between land titling and rural land transfer differs from one sample to another, and the samples have differing traits, those traits can be moderator variables in the relationship. In addition, meta-analysis can further explore the influence of situational factors by analyzing relevant moderating variables such as country and time based on the vast existing secondary database. Using meta-analysis technology, this study assesses the relationship between land titling and rural land transfer, transfer-in, and transfer-out in China and explores the roles of a range of moderator variables. These moderator variables include those at individual, household, and study timing levels.

(1) Individuals. Farmers' ages, education levels, and other factors significantly influence the rural land transactions in which they engage (Su et al., 2018a; Chikuni and Kilima, 2019; Peng et al., 2020). Studies have also shown that farmers of older age and lower cultural level have a deeper emotional attachment to their land, and land titling can help to further strengthen this endowment effect derived from emotion and further influence the farmers' land transfer behaviors (Zhong, 2013; Luo, 2017). However, some individual-level variables may contribute to the heterogeneity of the relevant conclusions. Therefore, this study first discusses the moderating effect of householder age and education level.
(2) Households play a critical role in China's agricultural production, based on various household-level variables such as labor force size, agricultural fixed asset value, and contracted land area (Zhang Y. et al., 2020; Ji et al., 2021). After land titling, farmers with different economic levels have various choices and the interaction between land titling and economic level has a significant impact on land transfer (Su et al., 2018b). Therefore, this study discusses the moderating effects of fixed asset value, total income, and agricultural income.
(3) Study timing. Land titling is a process of defining and confirming rights; it lasts for 10 years. During the land titling action, government behavior is "unstable" and thus affects farmers' expectations and behaviors (Ji et al., 2021), indicating

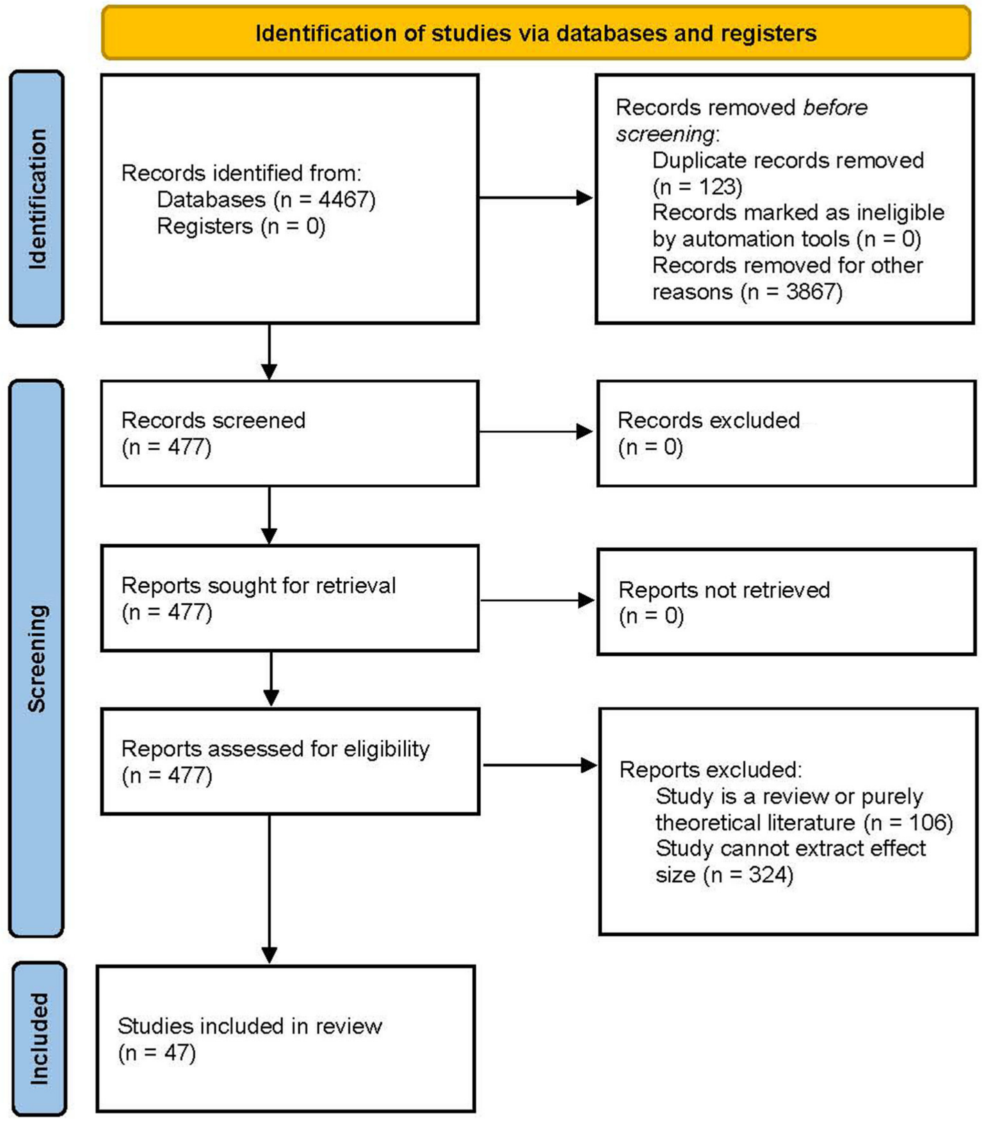


FIGURE 2
The PRISMA framework.

that the impact of a land titling varies with study timing, so the moderating effect of study timing is also discussed.

# Materials and methods

## Data collection

To ensure the accuracy and completeness of data, we comprehensively search both Chinese and English literature. Chinese literature is searched in CNKI's China Academic Journals Full-text Database, China Masters' Theses Full-text Database, and China Doctoral Dissertations Full-text Database, as well as the CQVIP and Wanfang databases, using the keywords "rural land titling" and "rural land transfer". English literature is mainly searched in several databases—Springer Link, Elsevier Science, EBSCO-ASP general subject full-text study literature, Emerald full-text journal, Wiley–Blackwell, ProQuest full-text journal, and ProQuest full-text master's and doctoral thesis databases—and Google Scholar using the keywords "land transaction," "land transfer," and "land titling". In order to avoid omissions in the literature, we conducted a second search on the reference literature of the searched related literature, i.e., manually searching all the Chinese and English reference literature related to the research topic in the sample literature, to ensure the comprehensiveness of the sample literature.

In combination with the requirements of the study topic and the meta-analysis method, studies included in the meta-analysis must meet the following conditions: (1) the target literature must contain keywords such as rural land titling, rural land transfer, and whether farmers have rural land titling subject to farmers' certificates of rural land titling and registration; (2) the studies must

TABLE 1 List of original studies included in the meta-analysis 1.

| No. | References | Outcome variable | Sample size ($N$) | Effect size ($K$) |
|---|---|---|---|---|
| 1 | Wang (2018) | Transfer | 315 | −0.214 |
| 2 | Liu and Luo (2018) | Transfer | 1,240 | 0.778 |
| | | Transfer-out | 1,240 | 0.709 |
| | | Transfer-in | 1,240 | 0.374 |
| 3 | Li (2020)** | Transfer | 5,967 | −0.008 |
| | | Transfer-out | 5,967 | 0.058 |
| | | Transfer-in | 5,967 | −0.084 |
| 4 | Ding and Zhong (2017) | Transfer | 405 | 0.32 |
| | | Transfer-out | 405 | 0.195 |
| | | Transfer-in | 405 | 0.427 |
| 5 | Feng et al. (2021) | Transfer | 9,596 | 0.081 |
| | | Transfer-out | 9,596 | 0.028 |
| | | Transfer-in | 9,596 | 0.129 |
| 6 | Zhu and Yang (2019) | Transfer-out | 9,165 | 0.08 |
| 7 | Liu and Luo (2018) | Transfer | 2,738 | 0.036 |
| 8 | Lin et al. (2016) | Transfer-out | 1,444 | 0.05 |
| 9 | He et al. (2016) | Transfer-out | 9,723 | 0.037 |
| 10 | Yu (2016) | Transfer | 287 | 0.232 |
| 11 | Li (2018) | Transfer | 8,670 | 0.025 |
| 12 | Zhou (2019) | Transfer | 275 | 0.215 |
| 13 | Li et al. (2018) | Transfer-out | 5,701 | 0.043 |
| | | Transfer-in | 5,701 | −0.011 |
| 14 | Xu (2019) | Transfer-out | 14,260 | 0.014 |
| | | Transfer-in | 14,260 | 0.014 |
| 15 | Han et al. (2019) | Transfer-out | 299 | 1.505 |
| | | Transfer-in | 299 | −2.161 |
| 16 | Cheng et al. (2016) | Transfer-out | 5,920 | 0.06 |
| | | Transfer-in | 5,920 | −0.014 |
| 17 | Shi et al. (2017) | Transfer-out | 612 | 0.006 |
| | | Transfer-in | 612 | 0 |
| 18 | Zhan and Zhang (2009) | Transfer-out | 142 | 0.146 |
| | | Transfer-in | 142 | −0.014 |
| 19 | Xu et al. (2017) | Transfer-out | 434 | 0.141 |
| | | Transfer-in | 420 | 0.059 |
| 20 | Xie et al. (2017) | Transfer | 231 | 0.031 |
| 21 | Liu et al. (2020) | Transfer | 1,030 | 0.387 |
| 22 | Wang (2019) | Transfer-out | 5,792 | −0.061 |
| | | Transfer-in | 5,792 | 0.029 |
| 23 | Shen (2021) | Transfer | 280 | 0.183 |
| 24 | Luo et al. (2017) | Transfer | 645 | −0.029 |
| 25 | Li (2020)** | Transfer | 5,967 | −0.036 |
| | | Transfer-out | 5,967 | −0.012 |
| | | Transfer-in | 5,967 | −0.048 |
| 26 | Huang et al. (2018) | Transfer | 14,321 | 0.06 |
| | | Transfer-out | 14,321 | 0.098 |
| | | Transfer-in | 14,321 | 0 |
| 27 | Fu et al. (2016) | Transfer-out | 305 | 0.297 |
| | | Transfer-in | 305 | −0.026 |
| 28 | Cai (2018) | Transfer | 397 | 0.221 |
| 29 | Feng et al. (2020) | Transfer | 8,199 | 0.936 |
| | | Transfer-out | 8,199 | 0.879 |
| | | Transfer-in | 8,199 | 0.965 |
| 30 | Xu and Niu (2020) | Transfer-out | 9,377 | 0.013 |
| | | Transfer-in | 9,377 | −0.012 |
| 31 | Huang et al. (2018) | Transfer | 105 | 0.219 |
| 32 | Cai and Xia (2017) | Transfer | 622 | −0.285 |
| 33 | Klaus et al. (2011)** | Transfer-in | 1,302 | −0.047 |
| | | Transfer-out | 1,302 | 0.055 |
| 34 | Ji and Qian (2018) | Transfer | 7,168 | 0.124 |
| 35 | Lin et al. (2017) | Transfer-out | 5,481 | −0.003 |
| | | Transfer-in | 5,481 | −0.026 |
| 36 | Luo and Wan (2019) | Transfer-out | 2,795 | −0.034 |
| 37 | Xu et al. (2017) | Transfer-out | 4,411 | 0.052 |
| 38 | Yang and Li (2020) | Transfer-in | 4,363 | 0.028 |
| 39 | Han and Liu (2019) | Transfer-out | 294 | 0.15 |
| | | Transfer-in | 294 | −0.014 |
| 40 | Feng and Zhong (2018) | Transfer-in | 1,336 | −0.083 |
| 41 | Liu and Xu (2016) | Transfer | 200 | 0.749 |
| 42 | Chen (2006) | Transfer-out | 1,001 | −0.034 |
| | | Transfer-in | 1,001 | −0.049 |
| 43 | Linxiu et al. (2019) | Transfer-out | 640 | −0.042 |
| | | Transfer-in | 640 | 0.092 |
| 44 | Klaus et al. (2011)** | Transfer-out | 1,302 | 1.984 |
| | | Transfer-in | 1,302 | −1.7 |
| 45 | Yang (2016) | Transfer | 291 | 0.407 |
| 46 | Cheng et al. (2019) | Transfer-out | 10,287 | 0.0111 |
| 47 | Yang and Wang (2022) | Transfer-out | 26,397 | 0.01 |

**One literature contains two different studies.

be empirical, excluding purely theoretical and literature reviews; in addition, sample size, correlation, and other data indicators that can be converted into effect size must be reported in the articles; (3)

samples for different studies must be independent of each other. If the samples for two studies are the same or overlap, the study with more detailed reports or a larger sample size is included in the analysis. We retrieved 4,467 relevant papers. After paper screening, we had finally acquired a total of 47 papers, of which 39 were in Chinese, and 8 were in English. Based on this data collection process, we drew the PRISMA framework (Figure 2).

## Variables

We follow the methodology proposed by Stanley et al. to generate high-quality study data (Stanley et al., 2013). We use effect size to indicate the strength of the relationship between land titling and rural land transactions. The larger the effect size, the stronger the association between land titling and rural land transactions. Effect size in meta-analysis usually consists of a correlation coefficient between continuous variables or the mean difference between two groups of subjects in an experimental study. The calculation and coding of effect values adhere to the principle of "one sample, one effect value". If a single literature reports multiple independent and non-redundant samples, the corresponding effect values are separately calculated and coded for each sample. After coding is completed, different researchers re-calculate and code the data to ensure the accuracy of the data. Of course, some studies do not report these values but rather report $t$-test, $F$-test, or $\chi^2$-test values—we use the tools provided by Wilson to convert them. Our meta-analysis study used Comprehensive Meta Analysis (CMA) software for statistical analysis. Table 1 lists the literature included in this study and the effect sizes obtained from it. In Table 1, columns 1 and 6 display the study numbers, while columns 2 and 7 list the authors of the studies and their respective publication years. Columns 3 and 8 present the types of land transfer analysis for each study, and columns 4 and 9 indicate the sample sizes included in the studies. Finally, columns 5 and 10 show the corresponding effect sizes of each study, as analyzed by CMA software.

In addition, Table 2 provides the moderator variable definition. "Householder" encompasses both "Age" and "Level of education;" "Household" comprises "Household labor force," "Present value of agricultural fixed assets," and "Area of household contracted land;" "Timing" refers to "Publication time".

## Publication selection bias

Journals usually exhibit a preference for publishing articles with statistically significant results, while those with non-significant results are often more difficult to publish. As the majority of the literature included in this meta-analysis consists of journal articles, a potential publication bias should be taken into consideration. First, we check for serious publication selection bias by referencing the funnel plot proposed by Light and Pillemer (1984). Most studies on the effect of rural land titling on rural land transfer (Figure 3, the funnel plot for the effect of rural land titling on rural land transfer) and rural land transfer-in (Figure 4) have concentrated on the middle and upper parts of the funnel plot with left–right symmetry, indicating only a small possibility of publication bias in the studies on the effects of rural land titling on rural land transfer and rural land transfer-in. In the meta-analysis of the effect of rural land titling on rural land transfer-out (Figure 5), some studies are concentrated on the left side of the funnel plot, and the effect size of individual studies is far from the central axis of the funnel plot, indicating that some publication bias may exist in the studies on the effect of rural land titling on rural land transfer-out.

Further testing for publication bias in the studies is conducted using a classic fail-safe $N$. The classic fail-safe $N$-test refers to the number of missing papers required to reduce the cumulative effect size to an insignificant level-i.e., the greater the classic fail-safe $N$, the less likely it is that publication bias exists (Jiang et al., 2012; Xie et al., 2016). The classic fail-safe Ns for the relationships between rural land titling and rural land transfer, rural land transfer-out, and rural land transfer-in are 21,154, 3,908, and 268, respectively—i.e., the number of additional papers for the sample needed to disprove the important relationships between rural land titling and rural land transfer, rural land transfer-out, and rural land transfer-in. The three corresponding classic fail-safe Ns are much larger than the 5K + 10 standard ($K$ is the total effect size included in the literature; $K = 48$) (Jin et al., 2016; Wang et al., 2016) and much different from the study sample. This result suggests that there is little possibility of publication bias in our research conclusions.

## Heterogeneity test and model selection

### Heterogeneity test

In a meta-analysis, to determine whether there is a moderator variable between main effects, a heterogeneity test is usually used to see how much the effect size has changed. The heterogeneity test is carried out using an $I^2$-test and $Q$-test in this study. An $I^2-$test is the effect size variation as a percentage of the total variation: $0 \leq I^2 < 25\%$ indicates the absence of heterogeneity; $25\% \leq I^2 < 50\%$ indicates low heterogeneity; $50\% \leq I^2 < 75\%$indicates moderate heterogeneity; and $75\% \leq I^2 < 100\%$ indicates high heterogeneity (Higgins and Thompson, 2002). $Q$-test is a test based on the total variation test, that is, $Q$-value obeys the chi-square distribution. If $P < 0.05$, there is heterogeneity in effect size.

The results of the heterogeneity test are set out in Table 3. The $I^2$ value of land titling on transfer, transfer-out, and transfer-in is 99.663, 98.552, and 99.193%, respectively, and the effect size $Q$-test is significant ($p < 0.05$), indicating high heterogeneity between rural land titling and rural land transfer, rural land transfer-out, and rural land transfer-in in the meta-analysis. There is a potential moderator variable between the effects of rural land titling on rural land transfer, rural land transfer-out, and rural land transfer-in.

### Model selection

The heterogeneity test can also be used to select a meta-analysis model. The difference between the fixed-effect and random-effect models lies in their different hypotheses for reasons for the difference between conclusions: the fixed-effect model believes that there is only one real effect size in all studies, and the difference

TABLE 2 Definition of moderator variable.

| Variable | Variable coding | |
|---|---|---|
| Householder | Age | 0 = Young, age < 53.14; 1 = senior, age ≥ 53.14 |
| | Level of education | 0 = Low, primary school or below or years of education <7; 1 = high, junior high school or above or years of education ≥ 7 |
| Household | Household labor force (aged 16–65) | 0 = Less, household labor force < 1.70; 1 = more, household labor force ≥ 1.70 |
| | Present value of agricultural fixed assets (RMB) (original value of fixed assets such as household farm vehicles, tractors, threshing machines, and harvesters) | 0 = Low, present value of agricultural fixed assets <14,718.54; 1 = high, present value of agricultural fixed assets ≥ 14,718.54 |
| | Area of household contracted land (mu) (per capita household area * household size) | 0 = Small, area of contracted land < 21.47; 1 = large, area of contracted land ≥ 21.47 |
| Timing | Publication time (year) (difference from 2022) | 0 = Far, publication time <4.23; 1 = near, publication time ≥ 4.23 |

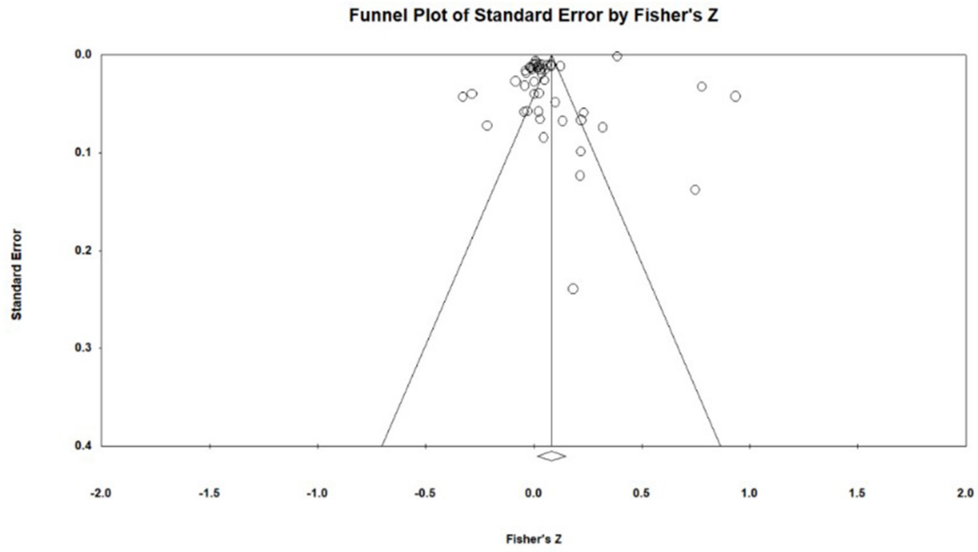


FIGURE 3
The funnel plot for the effect of rural land titling on rural land transfer.

between conclusions is solely due to sampling error; the random-effect model assumes that every study has its own real effect size and that the difference between conclusions is not solely due to sampling error (Borenstein et al., 2009). In general, if the $p$-value of the $Q$-test in the heterogeneity test is <0.01 and $I^2 > 50\%$, the random-effect model is more appropriate, and conversely, the fixed-effect model should be used (Hedges and Vevea, 1998).

# Results

## Main effect analysis

The results of the meta-analysis are shown in Table 4. According to the standards provided by Cohen (Cohen, 1992), a combined effect size <0.2 indicates a weak correlation between the two variables; a combined effect size between 0.2 and 0.5 indicates a moderate correlation; and a combined effect size >0.5 indicates a high correlation (Lipsey and Wilson, 2001). According to the results of the random-effect model, the combined effect sizes of rural land titling on rural land transfer and rural land transfer-out are 0.082 and 0.138, respectively, indicating that rural land titling has a slightly positive effect on rural land transfer and rural land transfer-out and is statistically significant (combined effect size < 0.2, $P < 0.05$). The results are consistent with earlier empirical study (Ye et al., 2018)—that is, there is a positive but weak correlation between rural land titling and rural land transfer and rural land transfer-out. The result is consistent with research that supports the rural land titling, which can facilitate the transfer of farmlands (Ma et al., 2015; Cheng et al., 2016, 2019; Liu et al., 2017; Xu et al., 2017; Ye et al., 2018; Wang, 2019). In addition, the combined effect size of rural land titling on rural land transfer-in is −0.03 and not statistically significant ($P > 0.1$), indicating that rural land titling has no significant effect on rural land transfer-in. The result neither supports the view that land titling promotes agricultural land transfer, nor supports the view that land titling suppresses agricultural land transfer. This might be because previous studies

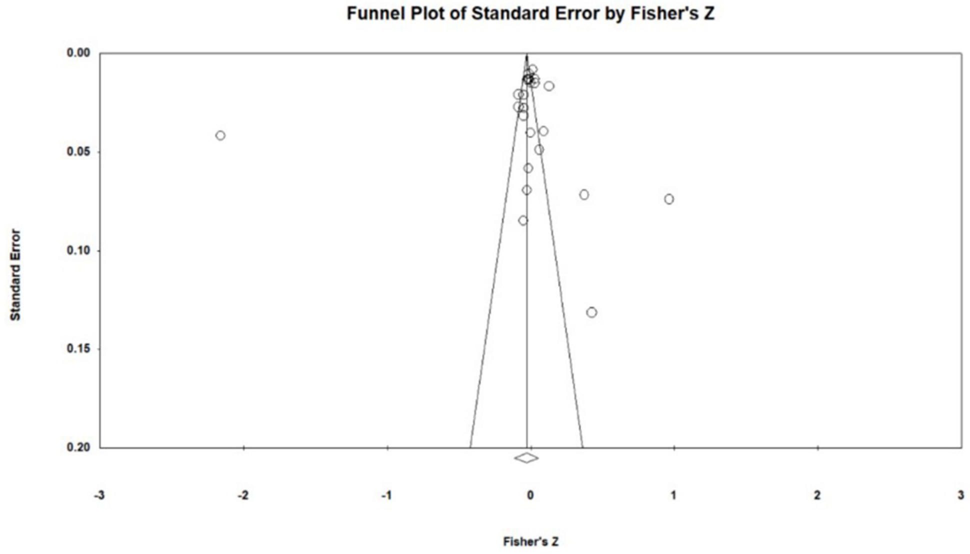


FIGURE 4
The funnel plot for the effect of rural land titling on rural land transfer-in.

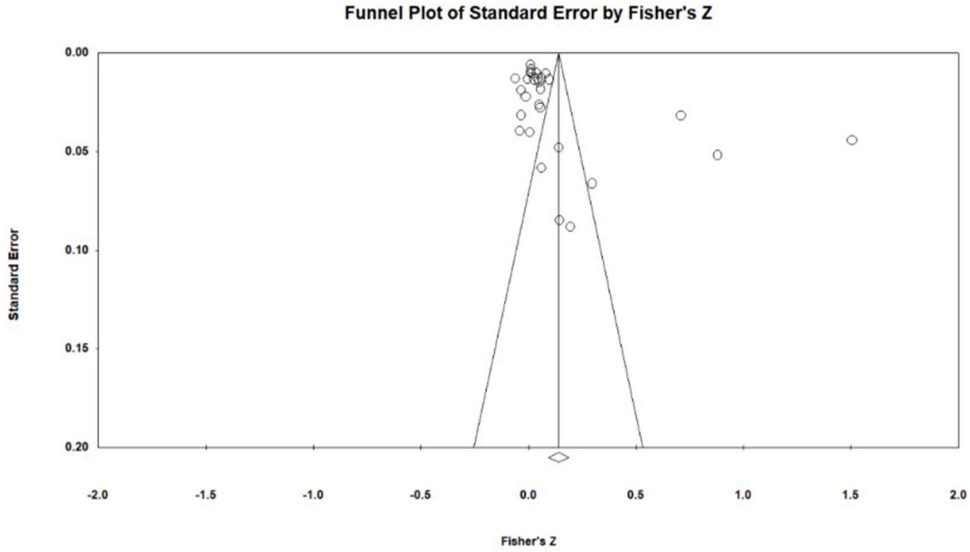


FIGURE 5
The funnel plot for the effect of rural land titling on rural land transfer-out.

have conflated land outflows and inflows without differentiating their heterogeneity.

## Moderating effect analysis

The main effect in Table 4 shows a very weak correlation ($K < 0.2$) between rural land titling and rural land transfer, rural land transfer-out, and rural land transfer-in, which may be due to a potential moderator variable that affects the correlation among the three. To explore the moderating effect and sources of heterogeneity of moderator variables, we use the methods proposed by Stanley and Jarrell (2005) and Zhang and Hu (2013) to carry out a meta-regression of the relationship between rural land titling and rural land transfer, rural land transfer-out, and rural land transfer-in, respectively. The moderating variables are grouped and categorized by mean, and the moderating effects are analyzed at three levels—householders, households, and publication time—with the results shown in Table 5.

In studies concerning the effect of rural land titling on rural land transfer, the effect size ($K$) of all moderator variables other than the present value of agricultural fixed assets ($K = 0.184$) is

<0.1. All variables other than the area of household contracted land are significant, indicating five moderator variables with a significantly weak positive effect on the relationship between rural land titling and rural land transfer. Only the moderator variable "area of household contracted land" has no significant effect, indicating that it is the only variable that does not play a role in regulating the relationship between rural land titling and rural land transfer. This may be due to the small area of farmers' household contracted land in some study samples, resulting in a less significant moderating effect.

In the study of the relationship between rural land titling and rural land transfer-out, all moderator variables have a significant moderate positive effect on the relationship between rural land titling and rural land transfer-out ($p < 0.1$), indicating that all moderator variables have a modulating effect on the study. At the householder level, the positive correlation between rural land titling and rural land transfer-out increases with senior aging and higher education levels of farmers. The specific magnitude of effects and the number of other moderating variables remain to be tested by subgroups. In addition, we can see that the moderator variables for rural land transfer-in are not significant. This suggests that rural land titling makes no contribution to rural land transfer-in, with the relationship unaffected by other situational factors.

## Robustness test: subgroup test

A subgroup test is used to study sources of heterogeneity and examine the robustness of the outcome of moderator variables to solve the problem of combined effect size in homogeneous heterogeneity and is typically used to handle heterogeneity in meta-analyses (Ding and Zhao, 2018). The operating principle of a subgroup test is to stratify each variable and establish subgroups for moderating variables. The moderating variables are generally grouped and classified by mean. At the same time, the effect sizes of all subgroups are combined, and statistical tests are conducted to verify the accuracy of the analysis of moderating variables by examining whether the combined effect sizes of all groups are significant and consistent in direction (Zhang, 2016). The subgroup test results of the effect of rural land titling on rural land transfer are shown in Table 6.

At the householder level, the effect size ($K$) of the senior age group = 0.036 and the effect size ($K$) of the low age group = 0.066 ($Q = 7.577$, $p < 0.01$), indicating that the age of farmers plays a significant role in moderating the relationship between rural land titling and rural land transfer, and the younger the householder is, the more he/she prefers to transfer rural land. The cause is that, as rural population increasingly moves into urban areas, the younger generation of farmers no longer have the same deep attachment to land as their fathers. Therefore, compared to the elderly farmers, the younger ones are more likely to transfer agricultural land after the land rights are secured.

At the household level, the present value of agricultural fixed assets ($Q = 2.877$, $p > 0.1$) indicate that the present value of agricultural fixed assets do not play a role in moderating the relationship between rural land titling and rural land transfer, and the reason may be that the farming size of sample farmers in some studies is small, there are few agricultural fixed assets, farmers mainly engage in household operations, and the quantity and use of agricultural assets tend to be consistent, leading to an insignificant moderating effect.

The area of household contracted land ($Q = 6.501$, $0.05 < p < 0.1$), the effect size ($K$) for farmers with more contracted land and less contracted land is 0.11 and 0.067, indicating that the more contracted farmland has a stronger positive relationship between rural land titling and rural land transfer, and a greater preference for transferring more farmland. The cause of this result might be that farmers operating on a larger scale of farmland have more incentives to further expand their operations through land transfer and thus gain more economic benefits. On the contrary, for small-scale farmers, there is no significant effect on the economic benefit either from entering or leaving after their rights are confirmed.

The household labor force ($Q = 10.485$, $p < 0.01$), and the effect size ($K$) of more household and less household labor forces is 0.138 and −0.045, respectively, and the significant difference between the two shows that household labor force plays a significant role in moderating the relationship between rural land titling and rural land transfer, and the more household labor force a household has, the stronger the positive relationship between rural land titling and rural land transfer is, and the more likely it is for the household to transfer rural land; however, households with less labor force play an inhibitory role in the relationship between rural land titling and rural land transfer, and are not willing to transfer rural land; and (3) publication time ($Q = 1.489$, $p > 0.1$) does not play a role in moderating the relationship between rural land titling and rural land transfer. This result implies that,

TABLE 3 Results of heterogeneity test for land titling on land transfer.

| Outcome variable | Effect size | $I^2$ | $Q$ | $df$ | $P$-value |
|---|---|---|---|---|---|
| Land titling to transfer | 47 | 99.669 | 13,884.589 | 46 | 0.000 |
| Land titling to transfer-out | 30 | 98.552 | 2,003.279 | 29 | 0.000 |
| Land titling to transfer-in | 25 | 99.193 | 2,973.432 | 24 | 0.000 |

TABLE 4 Results of main effect analysis for land titling on land transfer.

| Main effect | Effect size | Combined effect size ($K$) | Ll | Ul | $z$-statistical value | $p$-value |
|---|---|---|---|---|---|---|
| Land titling to transfer | 47 | 0.082 | 0.015 | 0.148 | 2.387 | 0.017 |
| Land titling to transfer-out | 30 | 0.138 | 0.091 | 0.184 | 5.783 | <0.01 |
| Land titling to transfer-in | 25 | −0.03 | −0.115 | 0.055 | −0.695 | 0.487 |

In the main effects, the mean value of the combined multiple effects of rural land titling on rural land transfer, rural land transfer-out, and rural land transfer-in is taken.

TABLE 5 Moderating effect analysis for land transfer.

| Moderator variable | | Transfer | | | | | Transfer-out | | | | | Transfer-in | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Combined effect size (*K*) | se | *Z* | *P* | *N* | Combined effect size (*K*) | se | *Z* | *P* | *N* | Combined effect size (*K*) | se | *Z* | *P* | *N* |
| Householder | Age of householder | 0.044 | 0.006 | 1.786 | 0.074 | 22 | 0.2 | 0.018 | 4.427 | <0.01 | 14 | −0.204 | 0.262 | −0.958 | 0.338 | 9 |
| | Education level of householder | 0.062 | 0.006 | 2.445 | 0.014 | 24 | 0.188 | 0.018 | 4.145 | <0.01 | 16 | −0.113 | 0.091 | −1.05 | 0.294 | 12 |
| Household | Household labor force | 0.082 | 0.006 | 2.929 | <0.01 | 15 | 0.233 | 0.018 | 4.911 | <0.01 | 12 | −0.188 | 0.118 | −1.504 | 0.133 | 9 |
| | Present value of agricultural fixed assets (RMB) | 0.184 | 0.02 | 2.725 | <0.01 | 6 | 0.187 | 0.03 | 2.154 | 0.031 | 4 | 0.062 | 0.005 | 1.559 | 0.119 | 3 |
| | Area of household contracted land (mu) | 0.071 | 0.042 | 1.197 | 0.231 | 16 | 0.203 | 0.023 | 3.566 | <0.01 | 11 | −0.196 | 0.13 | −1.423 | 0.155 | 9 |
| Timing | Publication time | 0.082 | 0.032 | 2.387 | 0.017 | 47 | 0.138 | 0.007 | 5.783 | <0.01 | 30 | −0.03 | 0.02 | −0.695 | 0.487 | 25 |

in terms of the research on land transfer in relation to land titling, the publication time of the research has not changed the relationship between the two. The reason may be that the existing research has not distinguished well between land inflow and outflow. Such a conflating approach is not conducive to clearly reflecting the relationship between the two variables of our concern.

Therefore, householder age and household labor force are significant in moderating rural land titling and rural land transfer, consistent with the moderating effect analysis results.

The subgroup test results of the relationship between rural land titling and rural land transfer-out are shown in Table 7.

(1) At the senior age group level, the age of a householder will significantly influence the effect of rural land transfer; the effect size ($K$) of senior age group $= 0.217$, effect size ($K$) of young age group $= 0.089$ ($Q = 6.93$, $p < 0.01$), which indicates that the more senior the householder becomes, the more he is inclined to transfer-out rural land. The effect size ($K$) of high education group $= 0.251$, and the effect size ($K$) of low education group $= 0.05$ ($Q = 6.584$, $p < 0.01$), which indicates that the educational years have a significant role in moderating the relationship between rural land titling and rural land transfer-out, and the more years of education, the stronger the positive relationship between rural land titling and rural land transfer-out is, and the more likely it is for the household to transfer-out rural land. The aforementioned results can be attributed to the fact that younger generations of farmers have a higher level of education, are more willing, and have easier access to employment outside of the agricultural sector, thus having a weaker emotional connection to the land. After land titling, new generations of farmers are more likely to exit their agricultural land compared to their elder counterparts.

(2) At the household level, the area of household contracted land ($Q = 3.671$, $p > 0.1$), indicating that the area of household contracted land is not significant; household labor force ($Q = 7.223$, $p < 0.1$) has a significant moderating effect, with more household labor force $K = 0.16$ and less household labor force $K = 0.372$, indicating that the less household labor force a household has, the stronger the positive relationship between rural land titling and rural land transfer-out is, and the more likely it is for the household to transfer-out rural land. The result is attributed to the fact that, in China where the level of agricultural mechanization is comparatively low, farming requires more labor input. Hence, for those households with a lower labor force, it is more advantageous to seek employment in the non-agricultural sector instead of possessing more rights in agricultural land. Consequently, after the land rights were secured, these households with a lower labor force were more inclined to transfer their agricultural land.

(3) In terms of article publication time, 66% of the effect sizes are derived after 2018—i.e., the vast majority of articles on rural land titling and rural land transfer-out were published after 2018, and the effect sizes of articles published before and after 2018 are 0.047 and 0.076 ($Q = 10.58$, $p < 0.1$),

TABLE 6 Subgroup test of the relationship between rural land titling and rural land transfer 2.

| Outcome variable | Moderator variable | | Class | Sample size | Effect size ($K$) | LL | UL | $Q$ | $p$ |
|---|---|---|---|---|---|---|---|---|---|
| Transfer | Householder | Age | Senior (≥53.14) | 13 | 0.036 | −0.031 | 0.103 | 7.577 | 0.056 |
| | | | Young (<53.14) | 8 | 0.066 | −0.013 | 0.144 | | |
| | | Level of education | High | 14 | 0.09 | 0.005 | 0.174 | 4.481 | 0.214 |
| | | | Low | 8 | −0.003 | −0.069 | 0.063 | | |
| | Household | Household labor force | More (≥1.70) | 11 | 0.138 | 0.061 | 0.213 | 10.485 | <0.01 |
| | | | Less (<1.70) | 4 | −0.045 | −0.126 | 0.037 | | |
| | | Present value of agricultural fixed assets (RMB) | High (≥14,718.54) | 2 | 0.123 | 0.101 | 0.146 | 2.877 | 0.237 |
| | | | Low (<14,718.54) | 4 | 0.201 | 0.02 | 0.369 | | |
| | | Area of household contracted land (mu) | Large (≥21.47) | 3 | 0.11 | −0.07 | 0.283 | 6.501 | 0.09 |
| | | | Small (<21.47) | 12 | 0.067 | −0.064 | 0.196 | | |
| | Timing | From 2018 | Far | 13 | 0.03 | −0.003 | 0.064 | 1.489 | 0.222 |
| | | | Near | 35 | 0.076 | −0.004 | 0.154 | | |

TABLE 7 Subgroup test of the effect of rural land titling on rural land transfer-out 3.

| Outcome variable | Moderator variable | | Class | Sample size | Effect size ($K$) | LL | UL | $Q$ | $p$ |
|---|---|---|---|---|---|---|---|---|---|
| Transfer-out | Householder | Age | Senior (≥53.14) | 12 | 0.217 | 0.121 | 0.309 | 6.93 | 0.031 |
| | | | Young (<53.14) | 2 | 0.089 | 0.006 | 0.17 | | |
| | | Level of education | High | 11 | 0.251 | 0.098 | 0.392 | 6.584 | 0.037 |
| | | | Low | 5 | 0.05 | 0.016 | 0.085 | | |
| | Household | Household labor force | More (≥1.70) | 8 | 0.16 | 0.078 | 0.239 | 7.223 | 0.027 |
| | | | Less (<1.70) | 4 | 0.372 | 0.056 | 0.62 | | |
| | | Present value of agricultural fixed assets (RMB) | High (≥14,718.54) | 0 | — | — | — | 0.415 | 0.519 |
| | | | Low (<14,718.54) | 4 | 0.187 | 0.017 | 0.347 | | |
| | | Area of household contracted land (mu) | Large (≥21.47) | 2 | 0.084 | −0.099 | 0.261 | 3.671 | 0.16 |
| | | | Small (<21.47) | 9 | 0.225 | 0.103 | 0.341 | | |
| | Timing | From 2018 | Far | 10 | 0.047 | 0.021 | 0.074 | 13.305 | <0.01 |
| | | | Near | 20 | 0.076 | 0.112 | 0.237 | | |

respectively, indicating that article publication time has a significant role in moderating the relationship between rural land titling and rural land transfer-out, and compared with early studies, articles published after 2018 show that farmers are more willing to transfer-out rural land, which is in line with the moderating effect acquired previously. The emergence of this outcome is attributable to the lagged effect of institutional influence on behavior. As a result, the effect of rights formalization on land transfer-out is more pronounced in recent studies. Therefore, the impact of land titling on land transfer-out is more significant in recent studies.

The subgroup test results of the effect of rural land titling on rural land transfer-in are shown in Table 8. The results show that education level and area of household contracted land are marginally significant ($0.05 < P < 0.1$), while all other moderator variables are marginally insignificant. The results are consistent with those shown in Table 8, indicating that the relationship between rural land titling and rural land transfer-in is not affected

TABLE 8 Subgroup test of the effect of rural land titling on rural land transfer-in 4.

| Outcome variable | Moderator variable | | Class | Sample size | Effect size ($K$) | LL | UL | $Q$ | $p$ |
|---|---|---|---|---|---|---|---|---|---|
| Transfer-in | Householder | Age | Senior (≥53.14) | 7 | 0.217 | −0.683 | 0.292 | 1.548 | 0.461 |
| | | | Young (<53.14) | 2 | −0.002 | −0.104 | 0.101 | | |
| | | Level of education | High | 10 | −0.128 | −0.356 | 0.113 | 5.399 | 0.067 |
| | | | Low | 2 | −0.041 | −0.09 | 0.008 | | |
| | Household | Household labor force | More (≥1.70) | 5 | 0.053 | −0.037 | 0.142 | 4.193 | 0.123 |
| | | | Less (<1.70) | 4 | −0.472 | −0.78 | 0.021 | | |
| | | Present value of agricultural fixed assets (RMB) | High (≥14,718.54) | 0 | — | — | — | 2.683 | 0.101 |
| | | | Low (<14,718.54) | 3 | 0.062 | −0.016 | 0.139 | | |
| | | Area of household contracted land (mu) | Large (≥21.47) | 2 | 0.193 | −0.218 | 0.545 | 5.278 | 0.071 |
| | | | Small (<21.47) | 7 | −0.299 | −0.555 | 0.008 | | |
| | Timing | From 2018 | Far | 8 | −0.043 | −0.063 | −0.023 | 0.136 | 0.712 |
| | | | Near | 17 | −0.021 | −0.138 | 0.097 | | |

by other situational factors. The result is attributed to the fact that land conversion is, in itself, an entrepreneurial behavior requiring higher capability, which is facilitated by higher education after the land titling. Meanwhile, the incentive for further land expansion is more salient for those with larger landholdings than those with smaller ones, leading to more positive land conversion after titling. Thus, concerning the impact of land titling on rural land transfer, we only need to focus on rural land transfer-in rather than rural land transfer-out.

To visualize the impact of each potential moderator variable on the relationship between rural land titling and rural land transfer, the results of the subgroup test have been visualized (Figure 6). Some obvious moderator variables are selected for analysis in the moderating effect illustrations. Specifically, the slope in the grouping illustration of each moderating variable represents the combined effect size of that moderating variable. Figure 6, which uses data from studies on the effect of rural land titling on rural land transfer, shows that farmer age, household labor force, and other moderator variables have a significant modulating effect on the main effect. Slopes in the various groups differ greatly, and the slopes of the household labor groups are opposites. This may offset the effect of rural land titling on rural land transfer and may be the main reason for only a weak positive correlation between rural land titling and rural land transfer-in the main effect analysis.

## Discussion

In China's traditional rural land property rights system, land transfer is not smooth, resulting in land abandonment and hindering the sustainable development of the rural economy. The Chinese government has completed the world's largest exercise in land titling to facilitate rural land transfers. However, the impact of China's land titling action, a costly project, on rural land transfer remains controversial in academia. To clarify the above debate, we have used the meta-analysis technology to explore the relationship between rural land titling and rural land transfer: (1) Rural land titling contributes to rural land transfer with a weak effect ($K = 0.082$, $P < 0.05$). (2) Rural land titling only contributes to rural land transfer-out with no effect on rural land transfer-in. Therefore, the so-called effect of land titling on rural land transfer is limited to rural land transfer-out. (3) The higher the educational level of farmers, the more senior the age of farmers, the more labor force in a household, the more agricultural fixed assets in a household, and the larger the area of contracted rural land, the stronger the effect that land titling has on rural land transfer-out. (4) Compared with early studies, land titling has a stronger effect on rural land transfer-out, according to recent studies.

Although the results of this study seem to support the idea that land titling promotes rural land transfer, the literature defines both transfer-in and transfer-out as transfer-in general terms. However, the empirical results indicate that rural land titling only contributes to rural land transfer-out, with no significant effect on rural land transfer-in. Thus, our conclusion will help clarify future studies on land titling and rural land transfer can focus on rural land transfer-out. This study also shows that the effect of land titling on rural land transfer is affected by situational factors such as education, age, labor force, agricultural fixed assets, and area of contracted rural land. We identify the sources of heterogeneity in the conclusions of existing literature and explore the hidden mechanisms that affect the relationship between rural land titling and rural land transfer.

The conclusion of this study helps us understand the reasons for the contradictory conclusions in the existing literature. On this basis, this study's conclusion helps us identify the possibility of improving rural land transfer by changing heterogeneity factors.

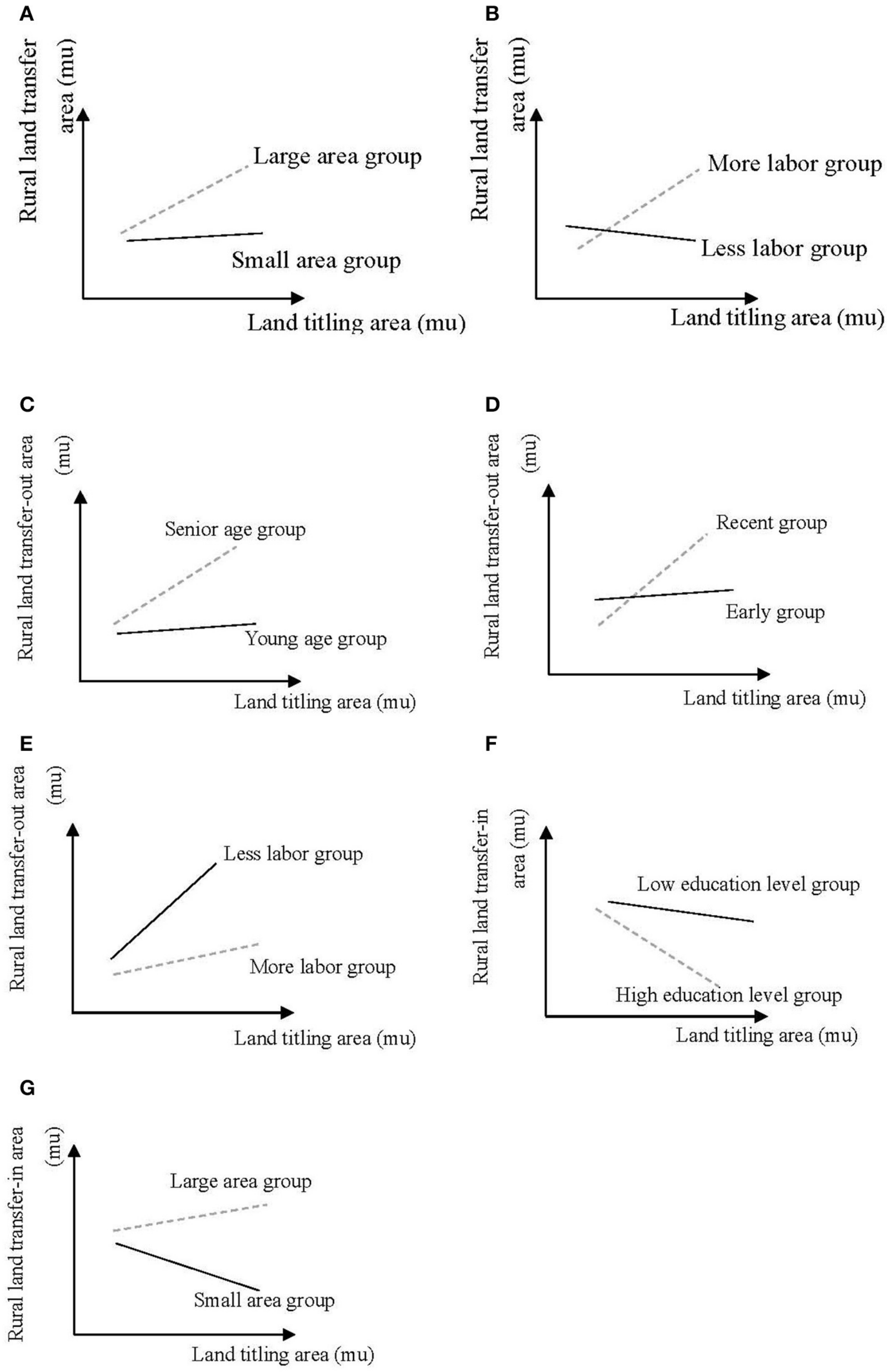


FIGURE 6
The moderating effect of rural land ownership confirmation on rural land transfer. **(A)** Area of contracted land (mu). **(B)** Household labor force. **(C)** Age. **(D)** Time of study. **(E)** Household labor force. **(F)** Level of education. **(G)** Area of contracted land (mu).

Therefore, from the perspective of policymakers, different strategies can be implemented for different groups to improve the land transfer rate and thus promote the sustainable development of the rural economy. The conclusion of this study also helps us identify topics for future studies to empirically test the effect of these situational variables by collecting data. This study also helps us treat rural land transfer dynamically—the role of land titling becomes more apparent over time, reflecting the long-term accumulation required for the definition of land titling and its implications.

Attention should be paid to the fact that both Chinese policy orientation and existing literature follow Coase's assumption, which states that the welfare growth could be achieved through the transfer of land rights among farmers. However, the literature has shown that property rights are much more complex than the framework proposed by Coase, thus Ostrom's Bundle of Rights provides a more comprehensive framework to tackle the complexity of land rights (Ostrom, 1990; Schlager and Ostrom, 1992). Chinese rural communities are a collective, thus a diverse range of policies and a multi-level bundle of rights should be developed to satisfy the different needs of community in managing resources and land. The greatest significance of this bundle of rights lies in the fact that it takes into account aspects such as social, cultural, and environmental aspects and combines traditional laws and policies with the realities of local communities to construct a more inclusive and diversified bundle of land rights. This bundle may be beneficial to policy makers, local community members and resource managers, providing a more effective resource management system for local communities and thus helping to resolve the complexities of land rights. Therefore, when it comes to the process of land transfer in Chinese rural areas, policies that are in line with the interests of the local community should be formulated to improve the land transfer rate, taking into consideration traditional culture and social requirements, and a multi-level bundle of rights should be perfected to realize social equity and environmental sustainability.

Although this study further proves that rural land titling has a weak effect on rural land transfer, it has the following limitations. First, there is a trade-off in the selection of moderator variables. Many situational variables are discarded to obtain a greater sample size and achieve data-based manipulability. Second, most of the literature included in the meta-analysis is journal literature, with less unpublished and degree literature at home and abroad, so the unbalanced distribution of literature may affect the results of the main effect analysis.

## Conclusions

This paper explored the relationship between rural land titling and rural land transactions using meta-analysis technology and identified and discussed the potential situational variables affecting the relationship. The results show that (1) rural land titling has a weak promoting effect on rural land transactions; (2) rural land titling only facilitates rural land transfer-out, with no effect on rural land transfer-in; (3) educational level, age, labor force, agricultural fixed assets owned, and area of contracted rural land are all situational variables that affect the relationship between land titling and rural land transfer; and (4) the relationship between rural land titling and rural land transfer is dynamic, and the longer that land titling takes, the more obvious the relationship between them becomes. Overall, this study contributes not only to our clarification of the true relationship between rural land titling and rural land transactions but also to our identification of topics for future studies. For example, this study has identified the moderating variables that influence the relationship between land titling and land transfer, guiding us to focus on the research of these moderating variables in the future. In addition, the conclusions of this study will help policymakers develop and implement appropriate policies to promote sustainable rural economic development by increasing land transfer rates.

This research suggests that simplifying agricultural land property rights may not support a sustainable rural agricultural production system. Instead, policies should align with local communities' interests, consider traditional cultures and social needs, and refine multi-level rights combinations. Further research on rural land rights combinations in China is still necessary.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

Conceptualization, validation, writing—review and editing, and funding acquisition: LX and LL. Methodology: LX, JZ, and DK. Software: DK, WH, and JZ. Formal analysis: JZ. Writing—original draft preparation: LX and DK. Supervision and project administration: LL. All authors have read and agreed to the published version of the manuscript.

## Funding

This research was funded by National Social Science Fund of China, Grant No. 21BJY184.

## Acknowledgments

The authors are grateful to the reviewers and the editor for their extensive and constructive review comments, which helped improve the quality of this paper.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

# References

Baumgart-Getz, A., Prokopy, L. S., and Floress, K. (2012). Why farmers adopt best management practice in the United States: a meta-analysis of the adoption literature. *J. Environ. Manag.* 96, 17–25. doi: 10.1016/j.jenvman.2011.10.006

Borenstein, M., Hedges, L. V., Higgins, J. P., and Rothstein, H. R. (2009). Effect sizes based on means. *Introd. Meta-analysis* 4, 21–32. doi: 10.1002/9780470743386.ch4

Boucher, S. R., Barham, B. L., and Carter, M. R. (2005). The impact of "market-friendly" reforms on credit and land markets in Honduras and Nicaragua. *World Dev.* 33, 107–128. doi: 10.1016/j.worlddev.2004.09.004

Bu, D., and Liao, Y. (2022). Land property rights and rural enterprise growth: Evidence from land titling reform in China. *J. elopment Econ.* 157, 102853. doi: 10.1016/j.jdeveco.2022.102853

Cai, J., and Xia, X. L. (2017). Can confirmation of farmland rights really promote the circulation of farmland by farmers?–An empirical analysis based on the survey data of the Guanzhong - Tianshui Economic Zone. *Arid Land Resour. Environ.* 31, 28–32. doi: 10.13448/j.cnki.jalre.2017.207

Cai, L. (2018). "*A study on the impact of rural land ownership confirmation on farmers' willingness to transfer agricultural land*," (master's thesis). Fujian Agriculture and Forestry University, FuJian, China.

Carter, M. R., and Olinto, P. (2003). Getting institutions "right" for whom? Credit constraints and the impact of property rights on the quantity and composition of investment. *Am. J. Agric. Econ.* 85, 173–186. doi: 10.1111/1467-8276.00111

Chamberlin, J., and Ricker-Gilbert, J. (2016). Participation in rural land rental markets in Sub-Saharan Africa: who benefits and by how much? Evidence from Malawi and Zambia. *Am. J. Agric. Econ.* 98, 1507–1528. doi: 10.1093/ajae/aaw021

Chen, L. X. (2006). "*A study on the behavior of rural land transfer in China*," (master's thesis). Nanjing Agricultural University, NanJing, China.

Cheng, L. G., Zhang, Y., and Liu, Z. B. (2016). Does rural land title contribute to the transfer of rural land in China. *Manag World.* 268, 88–98. doi: 10.19744/j.cnki.11-1235/f.2016.01.009

Cheng, W., Xu, Y., Zhou, N., He, Z., and Zhang, L. (2019). How did land titling affect China's rural land rental market? Size, composition and efficiency. *Land Use Policy* 82, 609–619. doi: 10.1016/j.landusepol.2018.12.037

Chikuni, T., and Kilima, F. T. (2019). Smallholder farmers' market participation and mobile phone-based market information services in Lilongwe, Malawi. *Electr. J. Inform. Syst. Dev. Count.* 85, e12097. doi: 10.1002/isd2.12097

Coase, R. (1960). The problem of social-costs. *J. Law Econ.* 3, 1–44. doi: 10.1057/9780230523210_6

Cohen, J. (1992). A power primer. *Psychol. Bull.* 112, 155–159. doi: 10.1037/0033-2909.112.1.155

Ding, F., and Zhao, H. (2018). Is the individual subjective well-being of gratitude stronger? A meta-analysis. *Adv. Psychol. Sci.* 26, 1749. doi: 10.3724/SP.J.1042.2018.01749

Ding, L., and Zhong, Z. B. (2017). Research on the impact of rural land contracting and management right confirmation on land circulation: empirical evidence from land right confirmation in Hubei Province. *Agric. Moderniz. Res.* 38, 452–459. doi: 10.13872/j.1000-0275.2016.0122

Du, X., and Zhang, G. (2022). The impact of land transfer on the income distribution of rural residents - empirical analysis based on the survey data of farmers in 10 provinces in 2020. *China Rural Econ.* 449, 107–126.

Fei, X. T. (1998). *Fertility System in Rural China*. Beijing: Peking University Press.

Feng, H. C., and Zhong, Z. B. (2018). Has the confirmation of agricultural land rights promoted the transfer of agricultural land–Empirical analysis based on data from three Provinces and Five Counties. *Study Pract.* 12, 26–37. doi: 10.19624/j.cnki.cn42-1005/c.2018.12.003

Feng, L., Hu, Y., Jiang, Y., and Lin, Y. (2020). Deepening and breakthrough of China's rural land transfer rights reform—analysis and suggestions based on the 2018 "1000 People 100 Villages" Survey. *Chin. Rural Econ.* 432, 2–21.

Feng, L., Li, Y. X., Jiang, Y., and Hu, Y. J. (2021). Land certificate, heterogeneity and agricultural land transfer: an empirical analysis based on the 2018 "1,000 People and 100 Villages" survey. *J. Public Admin.* 18, 151–164. doi: 10.16149/j.cnki.23-1523.20200826.001

Fu, J. T., Ji, Y. Q., and Hu, H. (2016). Whether the new round of contracted land title registration and certification promotes farmers' land transfer: empirical evidence from three counties (cities and districts) of Jiangsu Province. *J. Nanjing Agric. Univ. (Soc. Sci. Ed).* 16, 105–113+165.

Gao, J., Song, G., and Sun, X. (2020). Does labor migration affect rural land transfer? Evidence from China. *Land Use Policy* 99, 105096. doi: 10.1016/j.landusepol.2020.105096

Gould, K. A., Carter, D. R., and Shrestha, R. K. (2006). Extra-legal land market dynamics on a Guatemalan agricultural frontier: implications for neoliberal land policies. *Land Use Policy* 23, 408–420. doi: 10.1016/j.landusepol.2005.08.002

Guo, S., Lin, L., Liu, S., Wei, Y., Xu, D., Li, Q., et al. (2019). Interactions between sustainable livelihood of rural household and agricultural land transfer in the mountainous and hilly regions of Sichuan, China. *Sustain. Dev.* 27, 725–742. doi: 10.1002/sd.1937

Han, J. B., and Liu, S. Y. (2019). The impact of land ownership on rural labor transfer and employment: evidence from charles. *Popul. Econ.* 41–52.

Han, J. B., Liu, S. Y., and Zhang, S. F. (2019). Confirmation of agricultural land rights, land transfer and non-agricultural employment of rural labor: based on the perspective of incomplete contract theory. *Popul. Northwest* 40, 11–22. doi: 10.15884/j.cnki.issn.1007-0672.2019.03.002

He, X., Jiang, T., Guo, L. Y., and Gan, L. (2016). Research on the development of China's agricultural land transfer market and farmers' turnover farmland behavior-based on the survey data of farmers in 29 Provinces in 2013-2015. *Manag. World* 6, 79–89. doi: 10.19744/j.cnki.11-1235/f.2016.06.007

Hedges, L. V., and Vevea, J. L. (1998). Fixed-and random-effects models in meta-analysis. *Psychol. Methods* 3, 486–504. doi: 10.1037/1082-989X.3.4.486

Higgins, J. P., and Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statist. Med.* 21, 1539–1558. doi: 10.1002/sim.1186

Holden, S. T., Deininger, K., and Ghebru, H. (2007). Impact of land certification on land rental market participation in tigray region, northern ethiopia. *SSRN Elect. J.* doi: 10.2139/ssrn.1019996

Hong, W., and Luo, B. (2023). Can clear land rights change the mutual aid mechanism of the village society? *J. Agrotech. Econ.* 333, 4–16. doi: 10.13246/j.cnki.jae.2023.01.002

Huang, P. H., Li, Q., and Li, D. S. (2018). Can the new round of rights confirmation promote the circulation of agricultural land? *Econ. Latit.* 35, 44–49. doi: 10.15931/j.cnki.1006-1096.20180606.014

Hunter, J. E., and Schmidt, F. L. (2004). Methods of meta-analysis corrected error and bias in research findings. *J. Am. Statist. Assoc.* 20. doi: 10.2307/2289738

Ji, X. Q., and Qian, Z. H. (2018). How to promote the transfer of farmland management rights in a targeted manner? - An empirical analysis based on the survey data of 99 villages and 896 households in Jiangsu, Gui, Hubei and Heihei provinces (regions). *Manag. World* 34, 87–97. doi: 10.19744/j.cnki.11-1235/f.2018.03.008

Ji, Y. Q., Yang, Z. Y., Fang, C. L., and Wang, Y. N. (2021). From expectation to implementation: how does contracted land title affect farmers' decision-making on land transfer-out. *Chin. Rural Econ.* 439, 24–43.

Jiang, W., Li-long, Z., and Jun-zheng, F. (2012). Review and implementation process of meta-analysis in management research. *J. Zhejiang Univ. (Human. Soc. Sci.)* 42, 144–156.

Jin, Y., He, M., and Li, J. (2016). The relationship between meaning in life and subjective well-being in China: A meta-analysis. *Adv. Psychol. Sci.* 24, 1854. doi: 10.3724/SP.J.1042.2016.01854

Kahneman, D., Knetsch, J. L., and Thaler, R. H. (1990). Experimental tests of the endowment effect and the coase theorem. *J. Polit. Econ.* 98, 1325–1348. doi: 10.1086/261737

Klaus, D., Daniel, A. A., and Tekie, A. (2011). Impacts of land certification on tenure security, investment, and land market participation: evidence from Ethiopia. *Land Econ.* 87, 312. doi: 10.3368/le.87.2.312

Knetsch, J. L. (1989). The endowment effect and evidence of nonreversible indifference curves. *Am. Econ. Rev.* 79, 1277–1284.

Li, J. (2018). Confirmation of farmland rights, resource endowment constraints and farmland circulation. *J. China Univ. Geosci. (Soc. Sci. Ed.)* 18, 158–167. doi: 10.16493/j.cnki.42-1627/c.2018.03.031

Li, J. Y. (2020). How farmland tenure confirmation affects farmland circulation?-New evidence from China's household finance survey. *J. Zhongnan Univ. Econ. Law.* 2, 146–156. doi: 10.19639/j.cnki.issn1003-5230.2020.0021

Li, Y., Wu, W., and Liu, Y. (2018). Land consolidation for rural sustainability in China: practical reflections and policy implications. *Land Use Policy* 74, 137–141. doi: 10.1016/j.landusepol.2017.07.003

Light, R. J., and Pillemer, D. B. (1984). *Summing Up: The Science of Reviewing Research*. Cambridge, MA: Harvard University Press.

Lin, W. S., Qin, M., Su, Y. Q., and Wang, Z. G. (2017). How does the new round of rural land title affect rural land transfer?–evidence from the China health and pension tracking survey. *Village Econ.* 7, 29–43.

Lin, W. S., Qin, M., Zheng, S., and Wang, Z. G. (2016). The impact of asset exclusivity on the circulation of agricultural land after confirmation of rights. *J. South China Agric. Univ. (Soc. Sci. Ed.)* 15, 1–9.

Linxiu, Z., Yueming, C., and Yunli, B. (2019). The impact of the land certificated program on the farmland rental market in rural China. *J. Rural Stud.* 93, 165–175. doi: 10.1016/j.jrurstud.2019.03.007

Lipsey, M. W., and Wilson, D. B. (2001). *Practical Meta-Analysis.* Thousand Oaks, CA: Sage Publications, Inc.

Liu, C. F., He, Y. X., Luo, R. F., and Zhang, L. X. (2017). The impact of farmers' cognition and rural land property rights security on rural land transfer. *Econ. Survey* 34, 31–36. doi: 10.15931/j.cnki.1006-1096.2017.02.006

Liu, K., and Luo, M. Z. (2018). Confirmation of farmland rights, weakening of collective property rights and their impacts: a discussion based on fragmentation scenarios. *Econ. Latitude* 35, 44–50. doi: 10.15931/j.cnki.1006-1096.20180925.002

Liu, Y., Zhang, R., Li, M., and Zhou, C. (2020). What factors influence rural-to-urban migrant peasants to rent out their household farmland? Evidence from China's pearl river delta. *Land* 9, 418. doi: 10.3390/land9110418

Liu, Y. X., and Xu, H. Z. (2016). Research on the impact of rural land ownership confirmation on rural land transfer: based on the perspective of farmer differentiation. *J. Arid Land Resour. Environ.* 30, 25–29. doi: 10.13448/j.cnki.jalre.2016.142

Luo, B. L. (2017). Coase theorem: reflections and expansion—on the reform and choice of China's rural land transfer system. *Econ. Res. J.* 52, 178–193.

Luo, B. L. (2019). From defining property rights to implementing property rights: the past and future of the reform of China's rural land management system. *Issues Agricul. Econ.* 1, 17–31. doi: 10.13246/j.cnki.iae.2019.01.002

Luo, M. Z., Liu, K., and Zhu, W. J. (2017). Does confirmation of rights reduce farmland abandonment: an empirical analysis of PSM from questionnaire survey of farmers in Sichuan, Yu and Jinzhou Provinces. *Agricul. Technol. Econ.* 2, 15–27. doi: 10.13246/j.cnki.jae.2017.02.002

Luo, M. Z., and Wan, P. P. (2019). How does the confirmation of farmland rights affect the use of farmland? *Agricul. Moderniz. Res.* 40, 984–992. doi: 10.13872/j.1000-0275.2019.0073

Ma, X. L., Qiu, T. W., and Qian, Z. H. (2015). Rural land property rights security and farmers' participation in rural land transfer market: an empirical analysis based on survey data from Jiangsu, Hubei, Guangxi, and Heilongjiang. *Chin. Rural Econ.* 2, 22–37.

Miller, D., and Toulouse, J.-M. (1986). Chief executive personality and corporate strategy and structure in small firms. *Manag. Sci.* 32, 1389–1409. doi: 10.1287/mnsc.32.11.1389

Morewedge, C. K., and Giblin, C. E. (2015). Explanations of the endowment effect: an integrative review. *Trends Cogn. Sci.* 19, 339–348. doi: 10.1016/j.tics.2015.04.004

Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press.

Peng, K., Yang, C., and Chen, Y. (2020). Land transfer in rural China: incentives, influencing factors and income effects. *Appl. Econ.* 52, 5477–5490. doi: 10.1080/00036846.2020.1764484

Schlager, E., and Ostrom, E. (1992). Property-rights regimes and natural resources: a conceptual analysis. *Land Econ.* 68, 249–262. doi: 10.2307/3146375

Shen, X. Y. (2021). "*Research on the Impact of Land Ownership Confirmation on Farmers' willingness to transfer land*," (master's thesis). Yangtze University, HuBei, China.

Shi, M., Hermann, W., and Jikun, H. (2017). Smallholder participation in the land rental market in a mountainous region of southern china: impact of population aging, land tenure security and ethnicity. *Land Use Policy* 68, 33. doi: 10.1016/j.landusepol.2017.08.033

Stanley, T. D., Doucouliagos, H., Giles, M., Heckemeyer, J. H., Johnston, R. J., Laroche, P., et al. (2013). Meta-analysis of economics research reporting guidelines. *J. Econ. Surv.* 27, 390–394. doi: 10.1111/joes.12008

Stanley, T. D., and Jarrell, S. B. (2005). Meta-regression analysis: a quantitative method of literature surveys. *J. Econ. eys* 19, 299–308. doi: 10.1111/j.0950-0804.2005.00249.x

Su, B., Li, Y., Li, L., and Wang, Y. (2018a). How does nonfarm employment stability influence farmers' farmland transfer decisions? Implications for China's land use policy. *Land Use Policy* 74, 66–72. doi: 10.1016/j.landusepol.2017.09.053

Su, L., He, X., and Kong, R. (2018b). The influence of financial knowledge on farmers' land transfer behavior - analysis based on land titling regulation effect. *China Rural Econ.* 8, 17–31.

Sun, X. (2021). The causes of frequent rural land litigation: based on judicial practice research. *China Law Rev.* 37, 69–81.

Wang, F., Xie, H., and Li, H. (2016). Visual text or narration? Meta-analysis of the modality effect in multimedia learning. *Adv. Psychol. Sci.* 24, 335. doi: 10.3724/SP.J.1042.2016.00335

Wang, N. B. (2018). "*An empirical study on the impact of farmland ownership confirmation on farmers' willingness to transfer cultivated land*," (master's thesis). Guangxi University, GuangXi, China.

Wang, W., Wu, A. M., and Ye, F. (2018). "Land use reforms: towards sustainable development in China," in *Fiscal Underpinnings for Sustainable Development in China: Rebalancing in Guangdong*, eds E. Ahmad, M. Niu, and K. Xiao (Singapore: Springer), 29–51.

Wang, Y. (2019). What affects participation in the farmland rental market in rural China? Evidence from CHARLS. *Sustainability* 11, 7021. doi: 10.3390/su11247021

Xie, H., Wang, F., Zhou, Z., and Wu, P. (2016). Cueing effect in multimedia learning: a meta-analysis. *Acta Psychol. Sinica.* 48, 540–555. doi: 10.3724/SP.J.1041.2016.00540

Xie, L., Liao, J. H., and Hu, X. Y. (2020). Does agricultural scale management really contribute to fertilizer reduction? – evidence from meta-analysis. *J. China Agric. Univ.* 25, 172–185. doi: 10.19592/j.cnki.scje.371927

Xie, L., and Luo, B. (2013). Land ownership cognition and transfer disputes - questionnaire survey of village cadres. *China Rural Observer.* 1, 2–10+20+90.

Xie, W. B., Liu, J. Q., and Liu, G. Y. (2017). Research on the efficiency and causes of farmland transfer: based on 179 questionnaire surveys of farmers in Xinjiang. *China Agricul. Resour. Regional Plan.* 38, 56–63.

Xinhua News Agency (2014). *Opinions on Guiding the Orderly Transfer of Rural Land Management Rights and the Development of Appropriately Scaled Agricultural Operations*. Available online at: http://www.gov.cn/xinwen/2014-11/20/content_2781544.htm (accessed November 20, 2014).

Xinhua News Agency (2019). *Over 98% of Agricultural Operators in China Are Still Small-Scale Farmers*. Government of China. Available online at: http://www.gov.cn/xinwen/2019-03/01/content_5369755.htm (accessed March 1, 2019).

Xu, H., Zhao, Y., Tan, R., and Yin, H. (2017). Does the policy of rural land rights confirmation promote the transfer of farmland in China? *Acta Oecon.* 67, 643–672. doi: 10.1556/032.2017.67.4.7

Xu, H. Z., and Niu, K. (2020). Research on the influence of farmland confirmation on farmland circulation of farmers: based on the perspective of farmers' livelihood. *Res. Land Econ.* 1, 41–62.

Xu, M. Y. (2019). "*Research on the impact of rural land ownership confirmation on rural land transfer in China*," (master's thesis). Zhejiang University, ZheJiang, China.

Xu, Q., Yin, R., and Zhang, H. (2011). Economies of scale, scale returns and moderate scale management of agriculture - an empirical study of grain production in China. *Econ. Res.* 46, 59–71+94.

Yan, B. (2010). Land titling. *Econ. Syst. Reform.* 99–102.

Yang, G. L., and Wang, J. H. (2022). A new round of farmland ownership, farmland transfer, and scale management: evidence from CHFS. *Econom. Q.* 22, 129–152. doi: 10.13821/j.cnki.ceq.2022.01.07

Yang, H. L., and Li, H. P. (2020). The mechanism and policy implications of the impact of rural land ownership on farmers' income. *Reform Econ. Syst.* 4, 86–93.

Yang, L. (2016). "*Research on the Impact of Land Ownership Confirmation on Farmers' willingness to transfer land*," (master's thesis). Huazhong Agricultural University, HuBei, China.

Ye, J. (2015). Land transfer and the pursuit of agricultural modernization in China. *J. Agrarian Change* 15, 314–337. doi: 10.1111/joac.12117

Ye, J. P., Feng, L., Jiang, Y., Lang, Y., and Prostman, R. (2018). Land use right surveys in rural China in 2016–surveys of 17 provinces and recommendations. *Manag. World* 34, 98–108. doi: 10.19744/j.cnki.11-1235/f.2018.03.009

Yu, W. B. (2016). "*Research on the differences and influencing factors of rural land transfer intention under the background of farmer differentiation*," (master's thesis). Nanjing Agricultural University, NanJing, China.

Zhan, H. P., and Zhang, L. X. (2009). Family security, labor structure and land transfer of rural households: an empirical study based on 142 rural households in Jiangsu Province. *Resour. Environ. Yangtze River Basin* 18, 658–663. doi: 10.3969/j.issn.1004-8227.2009.07.012

Zhang, L., Cheng, W., Cheng, E., and Wu, B. (2020). Does land titling improve credit access? Quasi-experimental evidence from rural China. *Appl. Econ.* 52, 227–241. doi: 10.1080/00036846.2019.1644446

Zhang, Q. F., and Donaldson, J. A. (2013). China's Agrarian Reform and the Privatization of Land: a contrarian view. *J. Contemp. China* 22, 255–272. doi: 10.1080/10670564.2012.734081

Zhang, S. (2010). Land transfer and agricultural modernization. *Manag. World.* 202, 66–85+97. doi: 10.19744/j.cnki.11-1235/f.2010.07.008

Zhang, S. H. (2016). Subgroup analysis and sensitive analysis should be set up reasonably in meta-analysis. *Chin. J. Contemp. Neurol. Neurosurg.* 16, 1–2.

Zhang, X., and Hu, L. N. (2013). A Study on the boundary conditions of the relationship between the entrepreneurial orientation and the business performance. *Manag. World.* 6, 99–110+188. doi: 10.19744/j.cnki.11-1235/f.2013.06.008

Zhang, Y., Halder, P., Zhang, X., and Qu, M. (2020). Analyzing the deviation between farmers' Land transfer intention and behavior in China's impoverished mountainous Area: A Logistic-ISM model approach. *Land Use Policy* 94, 104534. doi: 10.1016/j.landusepol.2020.104534

Zhong, W. J. (2013). Endowment effect, cognitive hallucinations, and transaction costs: a Guangdong questionnaire for farmers on rural land management right transfer. *South China J. Econ.* 3, 13–22. doi: 10.19592/j.cnki.scje.2013.03.002

Zhou, H. Y. (2019). "*Research on the Impact of Rural Land Ownership Confirmation on Farmers' willingness to transfer land*," (master's thesis). Yangtze University, HuBei, China.

Zhu, J. J., and Yang, X. L. (2019). Research on the impact of the new round of farmland rights confirmation on the quantity and quality of farmland circulation-Based on the data of China's Rural Household Longitudinal Survey (CRHPS). *Agricul. Technol. Econ.* 3, 63–74. doi: 10.13246/j.cnki.jae.2019.03.006

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 26 July 2023
DOI 10.3389/fsufs.2023.1202485

OPEN ACCESS

EDITED BY
Rupak Goswami,
Ramakrishna Mission Vivekananda Educational and Research Institute, India

REVIEWED BY
Owais Ali Wani,
Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, India
A. Amarender Reddy,
National Institute of Agricultural Extension Management (MANAGE), India
Jeetendra Prakash Aryal,
International Center for Biosaline Agriculture (ICBA), United Arab Emirates

*CORRESPONDENCE
Vinaya Kumar Hebsale Mallappa
✉ vinayakumarhm@uahs.edu.in

RECEIVED 08 April 2023
ACCEPTED 07 July 2023
PUBLISHED 26 July 2023

CITATION
Hebsale Mallappa VK and Pathak TB (2023) Climate smart agriculture technologies adoption among small-scale farmers: a case study from Gujarat, India.
*Front. Sustain. Food Syst.* 7:1202485.
doi: 10.3389/fsufs.2023.1202485

# Climate smart agriculture technologies adoption among small-scale farmers: a case study from Gujarat, India

Vinaya Kumar Hebsale Mallappa[1]* and
Tapan Bharatkumar Pathak[2]

[1]Department of Agricultural Extension, University of Agricultural and Horticultural Sciences, Shivamogga, Shimoga, India, [2]Division of Agriculture and Natural Resources, University of California, Merced, Merced, CA, United States

In India, 78% of farmers are small and marginal, cultivating only 33% of the arable land but producing 50% of the food grain; their vulnerability to climate change poses a significant threat to the country's food security. To enhance agricultural resilience, it is crucial to understand how these farmers perceive and integrate climate-smart technologies into their farming practices. A random sample of 240 farmers was selected for this study. An ex-post facto research design was employed to investigate farmers' awareness of and adoption of CSAT and identify the significant variables influencing their decisions. The results indicate that approximately 74 per cent of farmers had low to medium awareness of CSAT, while around 83 per cent had low to medium adoption rates. Several factors were found to be significantly correlated with farmers' awareness and adoption of CSAT, including education level, annual income, exposure to agricultural mass media, participation in extension programs, innovativeness, achievement motivation, risk orientation, and scientific orientation. Additionally, farmers faced various challenges in adopting CSAT, such as the high cost of inputs, limited knowledge about CSAT, and youth migration from rural areas. Based on the study's findings, farmers emphasized the importance of involving them in decision-making processes related to the development of climate-smart technologies. They also highlighted the need for a timely supply of inputs and field visits to successful farms as effective means to promote awareness and adoption of CSAT. The comprehensive analysis of associated factors and empirical findings presented in this study will benefit private sector organizations, government extension agents, academics, and policymakers. By gaining insights into the determinants of CSAT adoption, these stakeholders can focus their efforts more effectively on promoting widespread adoption. Additionally, this study can inform policy decisions regarding the allocation of government resources to combat climate change.

KEYWORDS

**agriculture, climate smart technologies, farmers, path analysis, socio-psychological factors**

## Introduction

Nine billion people must be fed by 2050, which will require an additional 70 per cent more food production (FAO, 2009; Godfray et al., 2010; Thomas, 2011). Global food security is increasingly threatened by climate change (Hebbsale Mallappa and Shivamurthy, 2021; Salerno et al., 2021). Climate change has several consequences, including rising temperatures, more frequent and intense extreme weather events, water shortages, rising sea levels, ocean acidification, land degradation, altered ecosystems, and a decline in biodiversity (Chand et al., 2015; FAO, 2017; Pathak et al., 2018; Raza et al., 2019; Hatfield et al., 2020; Weiskopf et al., 2020). The IPCC report, released in 2019, highlights the significant role of land degradation as a contributing factor to climate change. The report emphasizes that land degradation leads to increased greenhouse gas emissions and reduced carbon uptake rates, exacerbating the effects of climate change (Shukla et al., 2019). These factors could seriously threaten agriculture's ability to produce and feed the most vulnerable population (resource-poor small-scale farmers) and delay achieving sustainable development goals (Vågsholm et al., 2020). Research organisations, educational institutions, line departments, NGOs, and policymakers must cooperate to reduce agriculture's contributions to climate change (GHG emissions) and involve agriculture and allied sectors in finding solution for rapidly changing environmental conditions (Smith et al., 2014).

Climate variability plays a crucial role in shaping food production and farmers' income in Gujarat and Indian agriculture (Khatri-Chhetri et al., 2016). Nearly 60 per cent of yield variability can be attributed to climatic fluctuations (Lobell and Gourdji, 2012; Aryal et al., 2018; Kukal and Irmak, 2018). The impacts of climate change are evident in the sowing and crop duration (Malhi et al., 2021), as well as the intensity and duration of heat and water stress experienced by agricultural systems (Burke et al., 2015). Higher average temperatures lead to reduced radiation interception and biomass production, hampering crop growth (Zhao et al., 2017). Additionally, above-optimal temperatures directly impact the crop physiological processes.

Gujarat, being an agriculturally diverse state in India, cultivates cotton, groundnut, rice, wheat, maize and millet as major crops. These crops are significantly impacted by climate change, leading to detrimental effects on yields and overall agricultural productivity (Aryal et al., 2020). For instance, studies have shown that increased temperatures and changing rainfall patterns negatively affect cotton production, with a projected decline of up to 14 per cent in yield by 2050 (Patel et al., 2015). Groundnut, another important crop, is highly sensitive to temperature and water stress, resulting in potential yield losses of 18–20 per cent under climate change scenarios (Malhi et al., 2021). Wheat, a staple crop, faces reduced yields due to rising temperatures, with estimated losses of 4–16 per cent by 2050 (Tesfaye et al., 2017a). Similarly, millets, which are drought-tolerant crops, are also vulnerable to changing rainfall patterns and increasing temperatures, leading to possible yield reductions of 10–20 per cent (Tiwari et al., 2022). These statistics emphasize the urgent need to implement climate change adaptation strategies and promote climate-resilient agricultural practices to safeguard the productivity and sustainability of the major cropping systems in Gujarat, Anand.

Climate-smart agriculture has demonstrated its efficacy in delivering tangible benefits to farmers. According to studies, the adoption of climate-smart practices can increase farmers' incomes by up to 30 per cent and enhance crop yields by 20–30 per cent (Musafiri et al., 2021). Moreover, the implementation of climate-smart techniques has the potential to reduce greenhouse gas emissions from agriculture (Khatri-Chhetri et al., 2016) by approximately 1.5 gigatons of carbon dioxide equivalent per year (Ouédraogo et al., 2019). Additionally, the improved soil management practices associated with climate-smart agriculture can enhance soil organic carbon content by 0.3–0.6 per cent annually, contributing to better soil health and nutrient availability (Aryal et al., 2015; Khatri-Chhetri et al., 2016). These statistics highlight the substantial economic, environmental, and climate change adaptation advantages that can be achieved through the widespread adoption of climate-smart agriculture (Holden et al., 2018).

The economic viability of the agricultural production system depends on the farmer's capacity to acclimatise their farming structures in opposition to the ecological and financial stress and vagaries (FAO, 2015a; Ministry of Agriculture and Farmers' Welfare, 2015). Adaptation strategies against climate change are essential for enhancing the supply of raw materials to attain economic security and to boost net farm revenue and the raw material supply from farming and allied businesses under the climate change regime (Parajuli et al., 2019; World Bank, 2020; Gustafson et al., 2021). FAO has initiated eight action programs, such as (1) irrigation and drought management, (2) climate-resilient agricultural systems, (3) sustainable forest and land management, (4) towards effective fisheries sector, (5) improving food and livelihood security by the reducing methane emissions, (6) effective planning and allocation of funds to promote adaptation strategies towards climate change, (7) genetic diversity and climate change, and (8) saving food and avoiding waste (FAO, 2015b). CSAT enhances yield and socio-economic conditions that align with reducing GHG emissions. Hence, new farming approaches will be required to ensure food security in the face of future climate change (IPCC, 2012; Philip and Leslie, 2014; Vinaya Kumar et al., 2017).

The farmers' level of efficiency in realising net revenue and utilising resources towards mitigating climate change is based on their adaptation strategies, such as crop choice, crop diversification, efficient irrigation systems, and the introduction of livestock components (Feliciano, 2019; World Bank, 2021). Land use and water resources have a significant impact on climate change in agriculture. There are various hurdles in mitigating climate change due to limited progress in drip irrigation, aerobic cultivation, and the use of drought-tolerant crop varieties with effective root systems, as well as the persistant burning of crop residues and the lack of tree planting in wastelands and unutilised cultivable lands (Lulia, 2012; Patle, 2021).

Despite the potential benefits, the adoption of CSAT is very low in India and other developing countries. To increase the adoption of CSAT, it is essential to enhance the understanding of small and marginal farmers regarding adaptation and mitigation strategies for climate change. The rate of diffusion strategies used by the development departments significantly impacts the speed at which technology is accepted and adopted.

Additionally, a number of factors have been linked to the awareness and adoption—or non-adoption—of technologies (Scott et al., 2008; Petronilla et al., 2016). Most studies have focused on one or two dimensions of household characteristics, asset base, and farm characteristics and their influence on the adoption of CSAT (Kurgat et al., 2020; Ayat et al., 2022; Negera et al., 2022). However, the influence pattern of these factors is often complex and context-specific, depending on the location and the technologies. Although psychological and situational factors play a significant role in technology adoption, no studies have focus on these factors and their influence on the awareness and adoption of CSAT. Hence, the present study is novel in understanding the complex relationship between the socio-psychological factors and their influence on the awareness and adoption of CSAT.

The small-scale farmers in the study area are frequently affected by erratic rainfall, waterlogging problems, salinity problems, incorrect agronomic practices, and flash floods during August–September, which have led to a decrease in field crop yields, ultimately affecting farmer profits (Shaw et al., 2005; Sivakumar and Stefanski, 2010; FAO, 2011; Mehta, 2019). Studying farmers' concerns regarding knowledge, adoption, and barriers to adopting CSAT will be extremely helpful in analysing the needs and requirements of farmers. With this backdrop, the study focuses on answering the following questions and hypotheses.

Questions:

1. What is the socio-economic and psychological profile of the farmers?
2. Are farmers aware of CSAT? If yes, then up to what extent are they aware of CSAT?
3. How well do farmers cope with changing climatic scenarios by adopting CSAT?
4. What personal, social, economic, and psychological characteristics influence the farmers' awareness of and adoption of CSAT?
5. Are farmers facing any difficulties in the adoption of CSAT to mitigate the ill effects of climate change? If yes, what are their suggestions for promoting CSAT?

Hyphotheses: ($H_0$):

1. There is no significant relationship between the socio-economic and psychological profile of the farmers and their awareness of and adoption of Climate-Smart Agriculture Technologies (CSAT).
2. ($H_0$): Farmers do not face any difficulties in the adoption of CSAT to mitigate the ill effects of climate change.

Understanding the significance of the study lies in its potential to provide evidence-based recommendations and guidelines for policymakers, extension agents, and other stakeholders involved in agriculture and rural development. By identifying the factors that influence farmers' awareness and adoption of CSAT, tailored interventions and support systems can be designed to enhance climate resilience in the agricultural sector. Furthermore, addressing the difficulties faced by farmers in adopting CSAT and incorporating their suggestions into strategies for promoting these technologies will ensure the relevance and effectiveness of future climate change mitigation initiatives.

This study's findings have the potential to inform policy decisions and resource allocation, enabling targeted investments in climate-smart agricultural practices and technologies. By bridging the gap between scientific research and on-the-ground implementation, this research contributes to the broader goal of sustainable and resilient agriculture in the face of climate change. Ultimately, the significance of this study lies in its potential to facilitate transformative changes in agricultural practices, leading to improved food security, livelihoods, and environmental sustainability in Gujarat, India, and beyond.

# Methodology

## Study area

The investigation was conducted in Anand district (22.3299° N, 72.6151° E) of Gujarat, India. The primary crops in the district are cotton, groundnut, rice, wheat, and tobacco. Other important crops include banana, mango, lemon, papaya and other seasonal vegetables. The average size of land holdings is 0.96 Ha, and small and marginal farmers own about 30.12% of the total land area. Climate factors include temperature and precipitation, which vary greatly from season to season, with summers typically being hot and winters typically being cool. The mean maximum temperature ranges between 28.4°C during January to around 41.8°C during May, while the mean minimum temperatures fluctuate between 11.7°C during January and 27°C during June. The long-term average annual rainfall is about 799 mm. The majority of precipitation occurs between June and September during the southwest monsoon. The district has a substantial network of canals (Mahi Right Bank Canal Command Area), and it is their major source of irrigation.

For the study, the district's Agriculture Officers (AOs) were consulted to assist in selecting talukas, and they were asked to suggest villages where farmers were partially or fully adopting CSAT. In order to choose 240 farmers from 16 villages for the study area, 15 farmers were randomly chosen from each of the selected villages. The investigation was carried out using the Ex-Post-Facto research design.

## Operationalisation of dependent variables

In this study, awareness refers to the first-hand information obtained by farmers about the CSAT in the farming system. Awareness is essential because it motivates individuals to obtain further information and take action. It represents the first step in the process of adoption.

A schedule was developed to assess farmers' awareness regarding CSAT. For this purpose, all relevant items about the CSAT were included, and the schedule was developed by referring to literature and consulting experts from multidisciplinary subjects of agriculture. The schedule consisted of 75 items with multiple choices, such as"Fully Aware," "Partially Aware," and "Not Aware." A score of two was assigned if the farmer was fully aware of an item, a score of one if the farmer was partially aware, and a score of zero if the farmer was not aware. The total score for each respondent was calculated accordingly. Based on their awareness scores using the mean and standard deviation, the respondents were divided into three groups.

Adoption in this study referred to the investigation of CSAT into farmers' farming practices. The technologies were selected from a package of practices and other literature reviews after discussions with subject matter specialists from Anand Agricultural University and the Gujarat state agriculture department. The scoring pattern for adoption was the same as mentioned in the awareness component.

The flow chat shows the relationship between climate change awareness, adoption of Climate-Smart Agriculture (CSA) practices, and farmers' income (Figure 1). It demonstrates the sequential steps involved, starting with increasing awareness about climate change and its impacts. From there, it shows farmers' decision-making process regarding adopting CSA practices, which can include various sustainable techniques. The flowchart highlights how adopting CSA practices can impact farmers' income through increased productivity and reduced production costs. It emphasizes the significance of

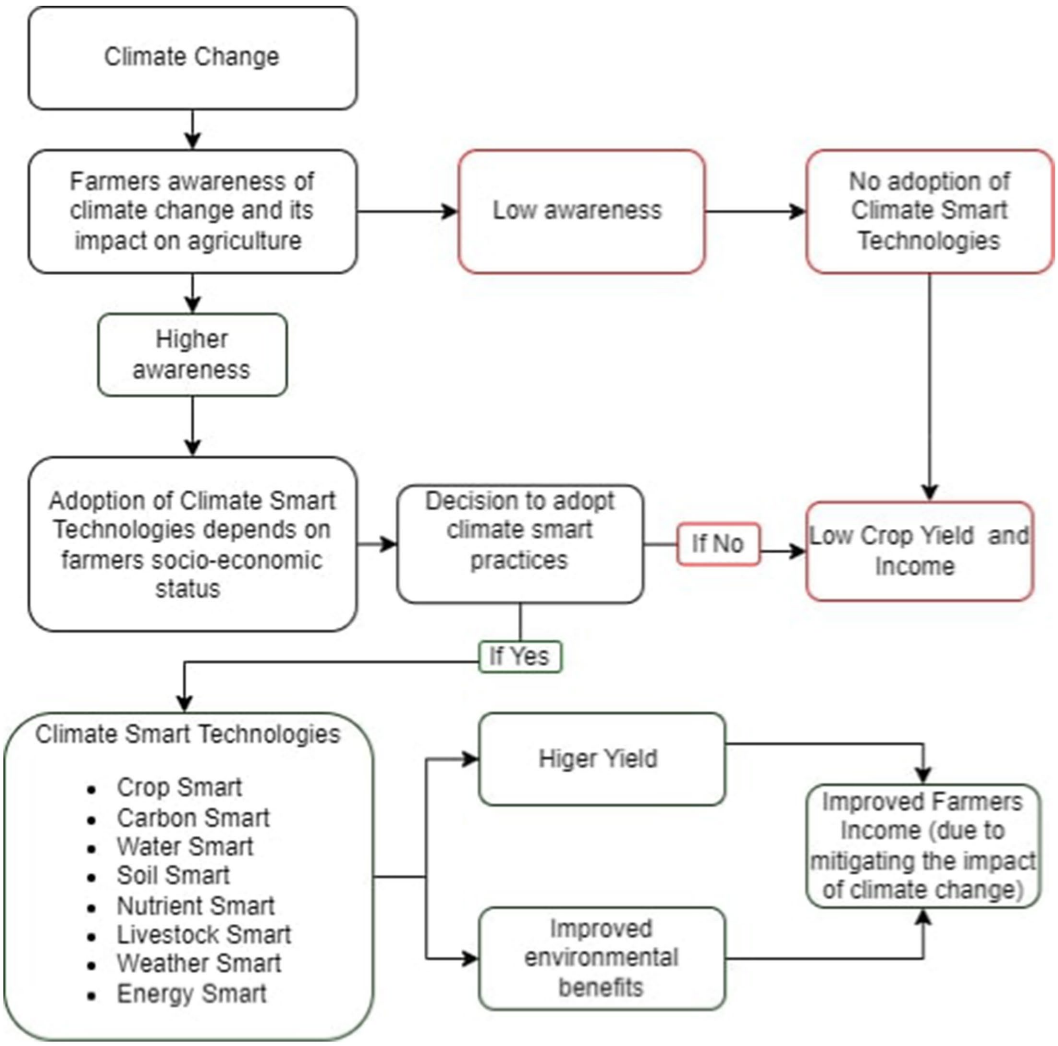


FIGURE 1
Flowchart presenting the relation among climate change awareness, adoption, CSA practices and farmers' income.

climate change awareness, adoption and sustainable farming practices in promoting farmers' income and resilience in the face of climate change challenges.

## Survey data and analysis

A standardised schedule comprising all the components of CSA technologies was developed with the help of agricultural extension, agronomy, and soil science experts. The interview schedule was pre-tested in a non-sample area to identify any unclear questions, and necessary corrections were made to the final interview schedule thereafter. The data were collected through in-person interviews using a structured interview schedule to gather qualitative and quantitative information about CSA. During the household interview, the primary decision-maker for the family was questioned about several CSA traits, specifically regarding their adoption in their farming system. The collected data were analysed using appropriate statistical tools, i.e., descriptive statistics, Spearman correlation, regression, principal component analysis, and path analysis.

## Path analysis

Path coefficient analysis (Wright, 1921) was used to determine the direct and indirect effects of predictive factors' on farmers' awareness and adoption of CSAT. The path co-efficient method extends the conventional partial regression coefficient method. The path analysis was carried out using SPSS software, and a diagram was developed by Drawings.net software. Path effects were obtained by solving the simultaneous equations set up for this purpose using the correlation matrix and considering one variable '1' to be influencing the other variable '1'. the simultaneous equation would be:

$$r_{yxi} = P_{yxi}r_{xixj}\ x\ p_{yxi} \qquad + \sum_{i.j=1}^{n}$$

For i = 1, 2, 3, ………., n
For j = 1, 2, 3, ………., n
i.e.,
$r_{yxi}$ = Correlation coefficient between $X_i$ with Y,

Pyxi = Direct effect of $X_i$ variable to Y variable, and

$\sum_{i.j=1}^{n} r_{xixj}\ x\ p_{yxi}$ = Indirect effect of the independent variable to a dependent variable *via.*, another independent variable.

# Results and discussion

## Socio-economic-psychological characteristics of the farmers

The information in Table 1 shows the detailed profile of respondents from the study area. Table 1 demonstrates that two-thirds of respondents (65.40%) were in the old age group, followed by the middle-aged (32.90%) category and the young (1.7%). Regarding educational level, secondary education accounts for the majority of responses (39.20%), followed by higher-secondary education (22.50%), degrees and above (20%), and primary education (18.30%). A large percentage of respondents (almost 71%) have a high degree of agricultural experience. More farmers have families that range in size from four to eight persons, followed by small families (34.17%) and large families (15.83%). Approximately 61 per cent of respondents belong to a joint family. Sixty-one and a half per cent of farmers claimed to work in agriculture and animal husbandry, while 31.25 per cent claimed to be engaged solely in the agricultural sector.

Table 1 shows that nearly two-thirds of the farmers (63.33%) are small farmers, followed by marginal farmers (36.37%). This could result from fragmented land ownership and the passing down of land from generation to generation. Over half of the respondents (51.25%) own low livestock, while high and medium livestock are owned by 25.42 per cent and 23.33 per cent of respondents, respectively.

Regarding annual income, 30 per cent of respondents are classified as high earners. Nearly two-fifths (39.60%) of respondents belong to a group with a medium degree of social participation. A higher percentage of respondents (42.90%) have low levels of exposure to agricultural media, followed by medium (35.40%) and high (21.70%) levels.

A little over two-fifths (42.50%) of the respondents have a medium level of engagement with extension services, followed by 33.30 per cent of farmers with a low level and 24.20 per cent with a high level. Two-fifths of respondents (40.40%) are classified as having a medium level of innovative proneness, followed by 32.50 per cent for low and 27.10 per cent for a high innovative proneness category.

Around 42 per cent of farmers have medium levels of achievement motivation, followed by 30.80 per cent with low and 27.10 per cent with high levels of achievement motivation. A higher percentage of farmers (46.67%) are low-risk-oriented and they also have a low level of scientific orientation (37.50%).

Psychological and economic factors significantly influence farmers' awareness and adoption of CSAT (Djufry et al., 2022; Kifle et al., 2022). However, the present study discovered that these factors, including personal, socio-economic, and psychological factors, fell into the low to medium range among the farmers. It is highly challenging to quickly improve the farmers' financial situation without addressing these traits. Nonetheless, farmers can be taught and have their positive attitudes toward CSA technologies can be changed through adequate education or capacity-building programmes, which

**TABLE 1** Personal, socio-economic and psychological characteristics of the farmers ($n = 240$).

| Characters | Category | Frequency | Per cent |
|---|---|---|---|
| Personal Variables | | | |
| 1. Age | Young (less than 35 years) | 4 | 01.70 |
| | Middle (between 35 to 55 years) | 79 | 32.90 |
| | Old (More than 55 years) | 157 | 65.40 |
| 2. Education | Primary education | 44 | 18.30 |
| | Secondary education | 94 | 39.20 |
| | Higher-Secondary education | 54 | 22.50 |
| | Degree and above | 48 | 20.00 |
| 3. Farming Experience | Very Low (less than 5 years) | 9 | 03.75 |
| | Low (between 6 to 10 years) | 27 | 11.25 |
| | Medium (between 11 to 15 years) | 33 | 13.75 |
| | High (more than 15 years) | 171 | 71.25 |
| 4. Family Size | Small (up to 4 members) | 82 | 34.17 |
| | Medium (between 5 to 8 members) | 120 | 50.00 |
| | Large (more than 8 members) | 38 | 15.83 |
| 5. Family Type | Nuclear Family | 94 | 39.20 |
| | Joint Family | 146 | 60.80 |
| Socio-economic Variables | | | |
| 6. Occupation | Agriculture | 75 | 31.25 |
| | Agriculture + livestock | 147 | 61.25 |
| | Agriculture + business | 18 | 07.50 |
| 7. Land Holdings | Marginal (below 1.0 ha) | 88 | 36.67 |
| | Small (1.0 to 2.0 ha) | 152 | 63.33 |
| 8. Livestock Possession | Low (≤ 2) | 123 | 51.25 |
| | Medium (3–5) | 56 | 23.33 |
| | High (≥6) | 61 | 25.42 |
| 9. Annual Income (₹) | ≤ 100,000 | 46 | 19.17 |
| | 100,001–200,000 | 51 | 21.25 |
| | 200,001–300,000 | 18 | 07.50 |
| | 300,001–400,000 | 26 | 10.83 |
| | 400,001–500,000 | 27 | 11.25 |
| | ≥500,001 | 72 | 30.00 |
| 10. Social Participation | Low | 85 | 35.40 |
| | Medium | 95 | 39.60 |
| | High | 60 | 25.00 |
| 11. Agricultural Mass Media Exposure | Low | 103 | 42.90 |
| | Medium | 85 | 35.40 |
| | High | 52 | 21.70 |

*(Continued)*

TABLE 1 (Continued)

| Characters | Category | Frequency | Per cent |
|---|---|---|---|
| 12. Extension Participation | Low | 80 | 33.30 |
| | Medium | 102 | 42.50 |
| | High | 58 | 24.20 |
| Psychological Variables | | | |
| 13. Innovative Proneness | Low | 78 | 32.50 |
| | Medium | 97 | 40.40 |
| | High | 65 | 27.10 |
| 14. Achievement Motivation | Low | 74 | 30.80 |
| | Medium | 101 | 42.10 |
| | High | 65 | 27.10 |
| 15. Risk Orientation | Low | 112 | 46.67 |
| | Medium | 65 | 27.08 |
| | High | 63 | 26.25 |
| 16. Scientific Orientation | Low | 90 | 37.50 |
| | Medium | 74 | 30.80 |
| | High | 76 | 31.70 |

can lead to their decision to try and adopt the CSA technologies in their farming systems (McNamara et al., 1991; Murage et al., 2015). Therefore, efforts in this regard must be undertaken to provide farmers with the tools they need to combat the adverse effects of climate change on their farms and livelihoods (Tama et al., 2021).

## Farmers' awareness of CSAT

The data in Table 2 revealed that for the first component, crop smart, the majority of the respondents (92.50%) were aware of short-duration varieties, followed by high-yielding varieties (90.83%), disease-resistant varieties (83.75%), pest-resistant varieties (83.33%), and mixed cropping (65.83%). Thus, it is evident that the farmers in the area were well aware of the varieties of crops such as banana, wheat, and other seasonal vegetables.

In the case of carbon smart, 83.75 per cent of the respondents acknowledged awareness of crop rotation awareness, followed by crop-livestock systems (70%), crop-tree-livestock systems (61.67%), agro-forestry systems (54.17%), and reduced tillage (49.58%).

According to the data in Table 2 regarding respondents' awareness of water smart practices, most of the farmers are aware of irrigation scheduling, followed by the choice of irrigation methods (76.67%), protective irrigation during critical crop stages (75.42%), micro-irrigation (7.17%), and high-value-low water use crops (61.25%).

Table 2 shows that 77.92 per cent of farmers were aware of soil smart technologies in relation to the statement “live barriers/fences,” whereas 67.08 per cent were aware of mulching, 61.67 per cent were aware of planting trees, and 55.42 per cent were aware of using cover crops.

In terms of nutrient smart awareness, 88.33 per cent of respondents were aware of compost, 82.5 per cent were aware of animal manure, 80.83 per cent were aware of green manuring, 80 per cent were aware of organic fertilizer, and 76.67 per cent were aware that bio-fertilizer was used in climate-smart farming.

According to the information on livestock smart awareness in Table 2, 84.17 per cent of farmers were aware of improved feed for livestock, followed by 78.75 per cent who were aware of concentrate feeding, 68.75 per cent who were aware of treating fodder, 67.50 per cent who were aware of improved livestock health, and 60.83 per cent who were aware of improved cow breed practices.

According to Table 2, when it comes to being weather-smart, 60.42 per cent of respondents are aware of ICT services to access weather information, while 50.83 per cent are aware of for seasonal weather forecasts. In addition, 37.50 per cent are aware of protected cultivation, and 34.58 per cent are aware of index-based insurance.

In the energy-smart category, 87.50 per cent of the farmers are aware of biogas plants, followed by 67.92 per cent of the farmers are aware of residue management, 56.25 per cent are aware of solar solutions, and 46.25 per cent are aware of minimum or zero tillage systems.

It is logical to conclude from the above results that practices that are complex, highly skill-oriented and difficult to understand are least known to farmers (Ravi and Ridhima, 2019; Muhammad and Marie, 2021). On the other hand, the practices that are simple, less costly, and have being practiced by their forefathers have higher awareness among farmers.

## Adaptation strategies regarding CSAT

According to the findings in the Table 2, high-yielding varieties have been adopted by 82.50 per cent of farmers, while disease-resistant varieties have been adopted by 79.17 per cent of respondents. Short-duration varieties have been adopted by 91.66 per cent of respondents, and pest-resistant varieties have been adopted by 77.50 per cent of respondents.

In the case of carbon smart, 70.42 per cent of the respondents have adopted crop rotation as an adaptation measures. Additionally, 64.17 per cent of farmers have adopted a crop-livestock system, 42.92 per cent have wisely used insecticides, 41.25 per cent have adopted reduced tillage, and 40.83 per cent have implemented a crop-tree-livestock system.

Regarding water-smart technologies, where 85.42 per cent of respondents have adopted calender-based irrigation scheduling, followed by 63.75 per cent who have used protective irrigation at crucial stages of the crop. Micro-irrigation has been adopted by 60.83 per cent of farmers, and high-value-low-water-use crop technologies have been adopted by 47,91 per cent of farmers.

In the case of soil-smart technologies, 66.66 per cent of farmers have adopted mulching, followed by 64.17 per cent who have adopted live barriers. Additionally, 52.92 per cent of them adopted tree planting, 48.33 per cent have adopted cover crops, and 47.50 per cent of farmers have adopted improved land leveling technologies in their farming systems.

Table 2 clearly indicates that compost technology has been adopted by 82.50 per cent of respondents in the case of nutrient smart technologies. Comparatively, 79.17 per cent have used animal

TABLE 2 The farmers' awareness and adoption of CSAT ($n = 240$).

| Sl. No. | | Awareness | | | Adoption | | |
|---|---|---|---|---|---|---|---|
| | Content | Frequency | % | Rank | Frequency | % | Rank |
| Crop Smart | | | | | | | |
| 1. | Short duration varieties | 222 | 92.50 | I | 220 | 91.66 | I |
| 2. | High yielding variety | 218 | 90.83 | II | 198 | 82.50 | II |
| 3. | Disease resistant varieties | 201 | 83.75 | III | 190 | 79.17 | III |
| 4. | Pest resistant varieties | 200 | 83.33 | IV | 186 | 77.50 | IV |
| 5. | Mixed cropping | 158 | 65.83 | V | 127 | 52.92 | VII |
| 6. | Drought tolerance varieties | 151 | 62.92 | VI | 132 | 55.00 | V |
| 7. | Direct seeded rice | 136 | 56.67 | VII | 129 | 53.75 | VI |
| 8. | Change in cropping pattern and calendar of planting | 130 | 54.17 | VIII | 92 | 38.33 | IX |
| 9. | Integrated farming system model | 122 | 50.83 | IX | 102 | 42.50 | VIII |
| 10. | Reducing plant population during stress season | 98 | 40.83 | X | 74 | 30.83 | XI |
| 11. | Contingency crop planning | 97 | 40.42 | XI | 83 | 34.58 | X |
| 12. | Seed and fodder banks | 86 | 35.83 | XII | 70 | 29.17 | XII |
| Carbon Smart | | | | | | | |
| 13. | Crop rotation | 201 | 83.75 | I | 169 | 70.42 | I |
| 14. | Crop-livestock systems | 168 | 70.00 | II | 154 | 64.17 | II |
| 15. | Crop-tree-livestock system | 148 | 61.67 | III | 98 | 40.83 | V |
| 16. | Agro-forestry systems | 130 | 54.17 | IV | 94 | 39.17 | VII |
| 17. | Reduced tillage | 119 | 49.58 | V | 99 | 41.25 | IV |
| 18. | Nitrogen-fixing trees on farms | 111 | 46.25 | VI | 79 | 32.92 | VII |
| 19. | Judicious use of insecticides | 100 | 41.67 | VII | 103 | 42.92 | III |
| 20. | Conservation agriculture | 73 | 30.42 | VIII | 49 | 20.42 | VIII |
| 21. | Cultivation of paddy through the SRI technique | 63 | 26.25 | IX | 42 | 17.50 | IX |
| Water Smart | | | | | | | |
| 22. | Calender based irrigation scheduling | 210 | 87.50 | I | 205 | 85.42 | I |
| 23. | Choice of irrigation methods | 184 | 76.67 | II | 153 | 63.75 | II |
| 24. | Protective irrigation during critical stages of crop | 181 | 75.42 | III | 146 | 60.83 | III |
| 25. | Micro-irrigation | 172 | 71.67 | IV | 115 | 47.91 | IV |
| 26. | High value-low water use crops | 147 | 61.25 | V | 114 | 47.50 | V |
| 27. | Improved drainage management | 125 | 52.08 | VI | 93 | 38.75 | VII |
| 28. | Water harvesting | 115 | 47.92 | VII | 70 | 29.17 | X |
| 29. | Cover crop method | 113 | 47.08 | VIII | 101 | 42.08 | VI |
| 30. | Judicious use of groundwater | 102 | 42.50 | IX | 82 | 34.17 | VIII |
| 31. | Laser land levelling | 94 | 39.17 | X | 71 | 29.58 | IX |
| 32. | Community-based water management | 78 | 32.50 | XI | 47 | 19.58 | XI |
| 33. | Contour farming | 76 | 31.67 | XII | 44 | 18.33 | XII |
| Soil Smart | | | | | | | |
| 34. | Live barriers/fence | 187 | 77.92 | I | 154 | 64.17 | II |
| 35. | Mulching (crop straw, plastic, residue) | 161 | 67.08 | II | 160 | 66.66 | I |
| 36. | Plantation of trees | 148 | 61.67 | III | 127 | 52.92 | III |
| 37. | Use of cover crops | 133 | 55.42 | IV | 116 | 48.33 | IV |
| 38. | Improved land levelling | 128 | 53.33 | V | 114 | 47.50 | V |
| 39. | Grass strips along the contour of waterways | 68 | 28.33 | VI | 66 | 27.50 | VI |
| 40. | Contour farming | 47 | 19.58 | VII | 45 | 18.75 | VII |

*(Continued)*

TABLE 2 (Continued)

| Sl. No. | | Awareness | | | Adoption | | |
|---|---|---|---|---|---|---|---|
| | Content | Frequency | % | Rank | Frequency | % | Rank |
| Nutrient Smart | | | | | | | |
| 41. | Use of compost | 212 | 88.33 | I | 198 | 82.50 | I |
| 42. | Use of animal manure | 198 | 82.50 | II | 190 | 79.17 | II |
| 43. | Green manuring | 194 | 80.83 | III | 179 | 74.58 | III |
| 44. | Organic fertiliser | 192 | 80.00 | IV | 166 | 69.17 | V |
| 45. | Bio-fertilizer | 184 | 76.67 | V | 174 | 72.50 | IV |
| 46. | Soil testing | 166 | 69.17 | VI | 158 | 65.83 | VI |
| 47. | Slow-releasing nitrogenous fertiliser as neem-coated urea | 152 | 63.33 | VII | 148 | 61.67 | VII |
| 48. | Scheduled fertiliser application | 151 | 62.92 | VIII | 141 | 58.75 | VIII |
| 49. | Intercropping with legumes | 145 | 60.42 | IX | 117 | 48.75 | IX |
| 50. | Integrated nutrient management | 126 | 52.50 | X | 112 | 46.67 | X |
| 51. | Site-specific integrated nutrient management | 119 | 49.58 | XI | 102 | 42.50 | XI |
| 52. | Leaf colour chart for checking nitrogen deficiency | 107 | 44.58 | XII | 93 | 38.75 | XII |
| 53. | Fertigation | 102 | 42.50 | XIII | 91 | 37.92 | XIII |
| 54. | Precision fertiliser | 74 | 30.83 | XIV | 70 | 29.16 | XIV |
| Livestock Smart | | | | | | | |
| 55. | Improved livestock feed | 202 | 84.17 | I | 157 | 65.42 | I |
| 56. | Concentrate feeding for livestock | 189 | 78.75 | II | 145 | 60.42 | II |
| 57. | Fodder treatment | 165 | 68.75 | III | 129 | 53.75 | IV |
| 58. | Improved livestock health | 162 | 67.50 | IV | 132 | 55.00 | III |
| 59. | Improved cow breeds | 146 | 60.83 | V | 110 | 45.83 | V |
| 60. | Improved buffalo breeds | 124 | 51.67 | VI | 103 | 42.92 | VI |
| 61. | Improved goat breeds | 49 | 20.42 | VII | 29 | 12.08 | VII |
| 62. | Improved poultry breeds | 33 | 13.75 | VIII | 28 | 11.66 | VIII |
| 63. | Improved sheep breeds | 32 | 13.33 | IX | 18 | 07.50 | IX |
| Weather Smart | | | | | | | |
| 64. | ICT services to access weather information | 145 | 60.42 | I | 123 | 51.25 | I |
| 65. | Seasonal weather forecast | 122 | 50.83 | II | 115 | 47.79 | II |
| 66. | Protected cultivation | 90 | 37.50 | III | 59 | 24.58 | V |
| 67. | Climate-smart housing for livestock | 73 | 30.42 | VI | 50 | 20.83 | VII |
| 68. | Weather-based crop advisory | 76 | 31.67 | V | 66 | 27.50 | IV |
| 69. | Climate analogues | 72 | 30.00 | VII | 54 | 22.50 | VI |
| 70. | Index based insurance | 83 | 34.58 | IV | 74 | 30.83 | III |
| Energy Smart | | | | | | | |
| 71. | Biogas plant | 210 | 87.50 | I | 108 | 45.00 | II |
| 72. | Residue management | 163 | 67.92 | II | 115 | 47.92 | I |
| 73. | Solar solutions | 135 | 56.25 | III | 58 | 24.17 | V |
| 74. | Minimum or zero tillage systems | 111 | 46.25 | IV | 59 | 24.58 | IV |
| 75. | Fuel efficient engines | 94 | 39.17 | V | 61 | 25.42 | III |

manure, 74.58 per cent have adopted green manure, 72.50 per cent have used biofertiliser, and 69.17 per cent have adopted organic fertiliser. Regarding livestock-smart technologies, 65.42 per cent of the farmers have adopted improved livestock feed, 60.42 per cent have adopted concentrate feeding for livestock, 55 per cent have adopted improved livestock health management practices, and 53.75 per cent have adopted fodder treatment practices in their livestock-based farming systems.

Table 2 shows that 51.25 per cent of respondents have adopted ICT services to obtain weather data, followed by 47.79 per cent who have adopted seasonal weather forecasts, and 30.83 per cent who have adopted index-based insurance.

According to the information in Table 2, around 48 per cent of the farmers have adopted residue management practices in their farming to manage the energy requirement, followed by 45 per cent who have adopted biogas plant technologies. Only 25.42 per cent of the respondents have adopted fuel efficient engines to meet the energy requirement in farming.

This kind of observation might be because farmers have resorted to using cost-effective and remunerative measures (Sivabalan and Nithila, 2018; Ravi and Ridhima, 2019; Muhammad and Marie, 2021; Mujeyi et al., 2021). Furthermore, other reasons such as extension agencies might not have educated the farmers about the CSAT, or they might have neglected these particular technologies due to their high financial investment.

A considerable number of farmers have adopted biofertilisers, organic fertilisers, weed management, and improved varieties. This certainly indicates a gradual change in the affective domain of farmers towards using fewer chemical control measures.

## Farmers' overall awareness level and adoption of CSAT in their farming system

The results presented in Figure 2 indicate the levels of awareness and adoption of Climate-Smart Agriculture Technology (CSAT) among farmers. Approximately 39 per cent of the farmers exhibited a low level of awareness, while 42.50 per cent had a low level of adoption of CSAT in their farming systems. On the other hand, a medium level of awareness was observed in about one-third (34.58%) of the farmers, and 40.42 per cent fell into the medium category of adoption. Interestingly, only one fouth (26.25%) and less than one-fifth (17.08%) of the farmers demonstrated a high level of awareness and adoption of CSAT, respectively. The Chi-square value of 127.809 indicates a significant correlation between the awareness and adoption of CSA technology.

Based on these findings, it is evident that there is room for improvement in enhancing farmers' awareness and adoption of CSA technology. The results suggest that efforts should be made by the government, line departments, and universities to focus on increasing farmers' awareness of CSAT. By doing so, farmers can develop a positive attitude towards CSA technology, which, in turn, will likely encourage active implementation of CSAT on their farms (Aryal et al., 2018; Mwungu et al., 2018). This emphasis on awareness-building can lead to a more widespread and effective adoption of climate-smart agricultural practices, ultimately contributing to the sustainability and resilience of farming systems in the face of climate change.

## Relationship between farmers' overall awareness of CSA technologies and their socio-psychological factors

A correlation test was conducted to examine the relationship between farmers' profile traits and their overall awareness of CSAT. The findings are presented in the Table 3. Eight factors, namely education, annual income, exposure to agricultural media, participation in extension programmes, innovative proneness, achievement motivation, risk-taking, and scientific orientation,were positively and significantly related to farmers' awareness levels at the 1 per cent level of significance. On the other hand, three factors, namely farming experience, family size, and family type,were negatively and significantly related to farmers' awareness level at 1 per cent level of significance. Other factors had tangential connections to farmers' awareness of CSA technologies.

Further, stepwise regression analysis was employed to determine the impact of the seven significantly associated variables on farmers' awareness of CSAT (as shown in Table 4). The findings revealed that these seven factors explained 48.30 per cent of the variation in farmers' CSAT awareness levels.

The results emphasize the importance of considering farmers' profile traits in efforts to enhance awareness of CSAT. By understanding the factors that influence farmers' awareness levels, policymakers and development agencies can design targeted

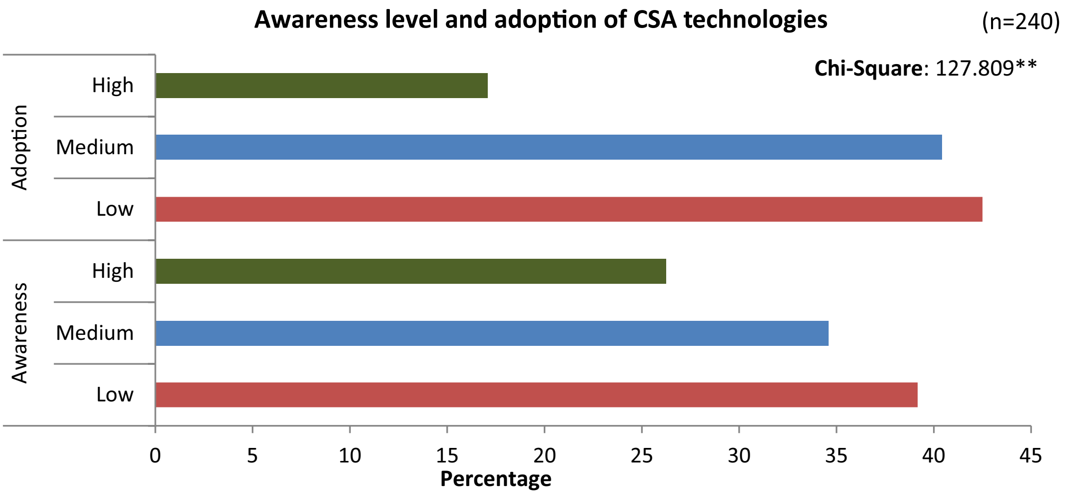


FIGURE 2
Overall farmers' awareness level and adoption of CSA technologies in their farming system. ** = significant at 0.01 per cent level.

interventions and support mechanisms to promote the adoption of climate-smart agricultural practices and contribute to the sustainable development of farming systems (Miheretu and Yimer, 2017; Chandio and Yuanshend, 2018; Mota et al., 2019).

## Relationship between profile characteristics of farmers and their overall adoption of CSAT

The findings of the correlation analysis between the profile characteristics of farmers and their overall adoption level are presented in Table 5. Among the 16 variables considered in the study education, occupation, annual income, social participation, exposure to agricultural media, participation in extension programmes, innovative proneness, achievement motivation, risk orientation, and scientific orientation were positively and significantly related to the adoption level at a 0.01 per cent level of significance. On the other hand, age, agricultural experience, family size, and family type were other factors that were negatively significant at a 1 per cent level of significance.

TABLE 3 Correlation (r) between the profile of the farmers and awareness of CSA technologies ($n = 240$).

| Sl. No. | Variable | Spearman ‘r’ value |
|---|---|---|
| 1. | Age | -0.100$^{NS}$ |
| 2. | Education | 0.302** |
| 3. | Farming Experience | −0.171** |
| 4. | Family Size | −0.291** |
| 5. | Family Type | −0.236** |
| 6. | Occupation | 0.063$^{NS}$ |
| 7. | Land Holding | 0.003$^{NS}$ |
| 8. | Livestock possession | −0.019$^{NS}$ |
| 9. | Annual Income | 0.316** |
| 10. | Social Participation | 0.022$^{NS}$ |
| 11. | Agricultural Mass Media Exposure | 0.294** |
| 12. | Extension Participation | 0.510** |
| 13. | Innovative Proneness | 0.256** |
| 14. | Achievement Motivation | 0.197** |
| 15. | Risk Orientation | 0.445** |
| 16. | Scientific Orientation | 0.373** |

NS = Non-significant. **Significant at 0.01 level.

Additionally, stepwise regression analysis was conducted to determine the impact of these 10 significantly associated variables on farmers’ adoption of CSAT (as shown in Table 6). The findings revealed that out of the 10 factors, four factors explained 41.90 per cent of the variation in farmers’ adoption of CSAT.

Based on these findings, it is crucial for governments and other development agencies to prioritize efforts in enhancing the profile characteristics that are significantly linked to farmers’ adoption of CSAT. By focusing on improving education levels, creating job opportunities, increasing annual income, promoting social participation, enhancing exposure to agricultural media, facilitating participation in extension programs, and fostering characteristics such as innovative proneness, achievement motivation, risk orientation, and scientific orientation, the overall adoption of CSAT among farmers can be significantly improved. Additionally, attention should be given to addressing the negative correlations associated with age, agricultural experience, family size, and family type, as these factors hinder farmers’ adoption and need to be carefully considered in adoption promotion strategies (Belay et al., 2017; Ouédraogo et al., 2019; Mujeyi et al., 2021).

## The determinants of farmers’ awareness and adoption of CSAT

The process of selecting elements to include in a model is a crucial issue in understanding the relationship between variable groupings. To address subjectivity and other estimation problems in conventional analysis like regression, the use of Principal Component Analysis (PCA) can provide theoretically and statistically sound approach. PCA can also aid in understanding the regression equation. The analysis of the findings is presented in Table 7.

The analysis revealed that the first component accounts for more than 18 per cent of the variations in the possible combinations of the 16 variables. When combined, the five factors explain over 60 per cent of the overall variation. The first component implicitly demonstrates the relationship between elements related to CSA technology and psychological components. The examination of the second primary

TABLE 4 Regression analysis demonstrating the relative significance of profile characteristics of farmers in determining their awareness of CSAT ($n = 240$).

| Sr. No. | Factors | Unstandardised Coefficients | | Standardised Coefficients | ‘t’ value |
|---|---|---|---|---|---|
| | | B | Std. Error | Beta | |
| 1. | Extension Participation | 0.659 | 0.128 | 0.273 | 5.140** |
| 2. | Risk Orientation | 1.054 | 0.169 | 0.316 | 6.238** |
| 3. | Agricultural Mass Media Exposure | 0.809 | 0.218 | 0.185 | 3.715** |
| 4. | Annual Income | 9.37E-06 | 0.000 | 0.258 | 4.480** |
| 5. | Innovative Proneness | 0.494 | 0.180 | 0.134 | 2.750** |
| 6. | Family Size | −0.457 | 0.195 | −0.116 | 2.341* |
| 7. | Land Holding | −1.010 | 0.469 | −0.121 | 2.152* |

$R^2 = 0.483$, $R^2$ adj = 0.467, F = 31.001**. **Significant at 0.01% level.
*Significant at 0.05% level.

component highlights the significance of economic factors (Abegunde et al., 2019; Mujeyi et al., 2019; Ouédraogo et al., 2019; Tran and Goto, 2019).

These findings highlight the importance of considering psychological and economic factors in promoting the adoption of CSA technology. Policymakers and development agencies should recognize the psychological aspects that influence farmers' decision-making processes, such as attitudes, motivations, and risk perceptions. Additionally, they should address the economic factors that affect the feasibility and profitability of adopting CSA technology.

## Path effects of farmers' profile traits on their awareness and adoption of CSA technology in their farming system

According to the data presented in Tables 8, 9; Figures 3, 4, involvement in extension programs had the greatest direct positive impact on farmers' awareness of CSA technologies, followed by risk orientation and annual income. On the other hand, the adoption of CSA technologies was significantly influenced by extension contact, media exposure, and annual income. Landholding, farming experience, and social participation had the least direct impact on awareness of CSAT among the farmers. The findings suggests that factors such as family size, land ownership, and farming experience had the least direct effects on the adoption of CSA technologies by farmers.

Tables 8, 9; Figures 3, 4 also revealed that scientific orientation, achievement motivation, and education were the key factors that had the greatest indirect positive effect on farmers' awareness of CSA technologies. The adoption of CSA technology was found to have the strongest and, most favourable indirect effects on extension participation, land ownership, and scientific orientation.

The data further indicated that annual income, risk orientation, and scientific orientation had the most significant indirect effects on farmers' awareness and adoption of CSA technologies (Nyasimi et al., 2017; Tesfaye et al., 2017b; Kurgat et al., 2020). To enhance farmers' awareness and adoption of CSA technology, it is important to consider the magnitude of the direct and indirect effects of different factors and the mediator role they play. Policymakers and development agencies should prioritize efforts to increase farmers' involvement in extension programs, improve access to agricultural media, and address income disparities.

Furthermore, promoting scientific orientation and achievement motivation through education and capacity-building initiatives can also have positive indirect effects on farmers' awareness and adoption levels. Moreover, the path analysis demonstrates that although only a few variables directly influence the dependent variables of awareness and adoption, the overall effect is predominantly driven by the interrelated nature of these variables (Marenya and Barrett, 2007). This highlights the complex and interconnected dynamics involved in shaping farmers' awareness and adoption of CSA technologies.

## Challenges faced by the farmers during the adoption of CSAT

Table 10 revealed that the majority of farmers (85.42%) reported that high input cost as the major restraining factor in the adoption of CSAT, followed by a lack of sufficient knowledge about the CSA technologies (75.42%), youth migration (78.50%), lack of awareness about climate change issues (70%), lack of farmers-friendly CSA technologies. These are the top five significant factors that limit farmers from adopting CSA technologies. Other constraints include the lack of legal and policy frameworks from the government (69.17%), uncertain returns (68.33%), absence of extension activities about CSA technologies (68.33%), lack of knowledge about adaptive practices of CSA (65.83%), poor information dissemination about the technologies (65.42%), non-availability of labour for the adoption of CSAT (65.00%), small landholding (64.58%), lack of access to credit (62.50%), absence of subsidies on planting materials (62.08%), delayed availability of inputs (61.67%), limited marketing access (59.58%), inadequate assistance from national and local authorities on climate-related issues (56.25%), lack of improved communication facilities (54.17%), lack of farmers' organisations (49.58%), lack of necessary transportation facilities (47.08%), poor supply of uniform electricity (39.58%), and lack of irrigation facilities (39.17%).

These findings are consistent with previous studies conducted by Headey et al. (2014), Long et al. (2016), and Tsige et al. (2020), indicating a consensus on the major constraints faced by farmers in adopting CSA technologies. To address these constraints and promote the adoption of CSA technologies, policymakers and development agencies should focus on several key areas. First, efforts should be made to reduce the input costs associated with implementing CSA practices. This can be achieved through targeted subsidies, access to affordable credit, and the provision of cost-effective CSA technologies.

Second, increasing farmers' knowledge and awareness of CSA technologies through capacity-building programs, training workshops, and extension services is crucial. Providing farmers with the necessary information and skills empowers them to make informed decisions and overcome barriers related to knowledge gaps (Ogato, 2014).

Third, addressing the issue of youth migration and attracting the younger generation to farming is vital. Creating favorable conditions, such as providing support for agricultural entrepreneurship, improving rural infrastructure, and offering incentives, can encourage youth involvement in farming and increase the adoption of CSA technologies.

Fourth, strengthening legal and policy frameworks related to CSA is essential. Clear regulations, supportive policies, and incentives can create an enabling environment for farmers to adopt sustainable agricultural practices.

Overall, understanding the key constraints reported by farmers in the adoption of CSA technologies is crucial for designing effective interventions. By addressing these barriers, policymakers and development agencies can facilitate the widespread adoption of CSA practices, leading to more resilient and sustainable agricultural systems.

## Farmers' suggestions to improve the adoption of CSAT

The results of Table 11 revealed that the majority of farmers (96.67%) believed that stakeholders should actively be involved in technological development. This was followed by the opinion that development organisations and line departments should ensure the availability of production inputs throughout the cropping season (87.08%). Other important factors mentioned were arranging visits to successful fields (83.75%), providing financial support for adoption and purchase of inputs (81.25%), demonstrating CSA technologies in villages (80.83%), and making improved crop variety seeds available in the village (77.08%).

These findings align with previous studies conducted by Jirata et al. (2016), Abera et al. (2020), and Hariharan et al. (2020), suggesting a consensus among farmers regarding the importance of stakeholder involvement and the measures needed to promote the adoption of CSA technologies.

To effectively address the farmers' perspectives and recommendations, it is crucial to raise awareness among the farming community about climate change and the advancements in CSA technologies. Farmers need to be informed and educated about the benefits and practices of CSA and the importance of sustainable land-use practices. Additionally, farmers should be encouraged to actively participate in technology development and decision-making processes, as their insights and experiences are vital for the successful implementation of CSA initiatives. It is particularly important to consider the specific requirements and challenges faced by small, marginal, and resource-poor farmers, who may require additional support and tailored approaches to ensure their inclusion in CSA programs.

TABLE 5 Correlation analysis between the profile of the farmers and the adoption of CSAT by farmers' ($n = 240$).

| Sl. No. | Variable | Spearman value ('r') |
|---|---|---|
| 1. | Age | −0.182** |
| 2. | Education | 0.255** |
| 3. | Farming Experience | −0.175** |
| 4. | Family Size | −0.300** |
| 5. | Family Type | −0.200** |
| 6. | Occupation | 0.182** |
| 7. | Land Holding | $0.116^{NS}$ |
| 8. | Livestock possession | 0.130* |
| 9. | Annual Income | 0.450** |
| 10. | Social Participation | 0.179** |
| 11. | Agricultural Mass-media Exposure | 0.312** |
| 12. | Extension Participation | 0.464** |
| 13. | Innovative Proneness | 0.221** |
| 14. | Achievement Motivation | 0.251** |
| 15 | Risk Orientation | 0.184** |
| 16. | Scientific Orientation | 0.219** |

NS = Non-significant. **Significant at 0.01 level.
*Significant at 0.05 level.

## Conclusion

1. The majority of farmers in the study area exhibit a high level of awareness and adoption of crop-smart practices, such as short-duration and high-yielding crop varieties, indicating their knowledge of improved agricultural techniques.
2. Farmers show relatively lower awareness and adoption levels in certain areas of climate-smart agriculture, such as energy-smart and weather-smart technologies. Continuous learning about CSAT, climatic information, and agro-advisory services should be prioritised for farmers, financial institutions, and input service providers. This will enhance farmers' capacity to adapt to climate change while also changing their perspectives on climate-smart farming. Although, our study focused on India, the conclusions drawn can be applicable to other countries that seek to increase agricultural output while minimising the negative impact of climate change.
3. It is evident that governments and other development agencies should prioritize efforts to enhance the profile traits that are significantly linked to farmers' awareness of CSAT. By focusing on improving education levels, increasing income opportunities, promoting exposure to agricultural media, facilitating participation in extension programs, and fostering characteristics such as innovative proneness, achievement motivation, risk-taking, and scientific orientation, the overall awareness of CSAT among farmers can be significantly improved. Additionally, attention should be given to addressing the negative correlations associated with farming experience, family size, and family type, as these factors hinder farmers' awareness and need to be carefully considered in awareness-building initiatives.
4. Constraints hindering the adoption of CSA technologies include high input costs, lack of knowledge, youth migration, and limited awareness about climate change issues. Addressing

TABLE 6 Regression analysis demonstrating the relative significance of profile characteristics of farmers in determining their adoption of CSAT ($n = 240$).

| Sr. No. | Factors | Unstandardised Coefficients | | Standardised Coefficients | 't' value |
|---|---|---|---|---|---|
| | | B | Std. Error | Beta | |
| 1. | Extension Participation | 0.790 | 0.133 | 0.314 | 5.921** |
| 2. | Annual Income | 1.38E-05 | 0.000 | 0.363 | 7.143** |
| 3. | Family Size | −0.802 | 0.209 | −0.196 | 3.832** |
| 4. | Agricultural Mass Media Exposure | 0.749 | 0.236 | 0.164 | 3.174** |

$R^2 = 0.419$., $R^2$ adj = 0.409, F = 42.345. **Significant at 0.01% level.

TABLE 7 Contribution of factors on awareness and adaption of CSAT ($n = 240$).

| Sl. No. | Components | Components | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| | Eigen root | **2.882** | **2.323** | **1.82** | **1.441** | **1.283** |
| | % Variation expressed | **18.011** | **14.521** | **11.376** | **9.007** | **8.016** |
| | Cumulative variation expressed | **18.011** | **32.532** | **43.908** | **52.915** | **60.93** |
| 1. | Age | −0.378 | −0.556 | 0.250 | 0.353 | 0.306 |
| 2. | Education | **0.571** | 0.179 | −0.215 | −0.029 | −0.370 |
| 3. | Farming Experience | −0.406 | −0.433 | 0.371 | **0.546** | 0.245 |
| 4. | Family Size | −0.513 | 0.097 | **0.518** | −0.187 | −0.398 |
| 5. | Family Type | −0.550 | 0.191 | 0.471 | −0.224 | −0.324 |
| 6. | Occupation | 0.019 | **0.609** | −0.166 | 0.244 | 0.176 |
| 7. | Land Holding | 0.118 | 0.392 | 0.359 | 0.503 | −0.281 |
| 8. | Livestock possession | −0.090 | 0.496 | 0.297 | 0.270 | 0.264 |
| 9. | Annual Income | 0.333 | **0.572** | 0.241 | 0.474 | −0.111 |
| 10. | Social Participation | 0.061 | 0.375 | **0.501** | −0.429 | 0.376 |
| 11. | Agricultural Mass Media Exposure | 0.397 | 0.260 | 0.128 | −0.411 | 0.257 |
| 12. | Extension Participation | **0.657** | −0.102 | 0.370 | −0.158 | 0.258 |
| 13. | Innovative Proneness | 0.293 | 0.004 | −0.074 | 0.263 | **0.575** |
| 14. | Achievement Motivation | 0.478 | −0.201 | 0.469 | −0.113 | −0.065 |
| 15. | Risk Orientation | **0.559** | −0.421 | 0.098 | 0.191 | −0.328 |
| 16. | Scientific Orientation | **0.575** | −0.462 | 0.377 | 0.065 | −0.096 |

Bold values mean important factors in each component.

TABLE 8 Path effect of selected characteristics of the farmers on awareness about CSA technologies ($n = 240$).

| Sr. No. | Factors | Total Direct effect | Total Indirect effect | Substantial effect | |
|---|---|---|---|---|---|
| | | | | 1 | 2 |
| X1 | Age | 0.0741 | −0.1744 | 0.0084 (X10) | 0.0073 (X7) |
| X2 | Education | 0.0896 | 0.2120 | 0.0680 (X15) | 0.0495 (X12) |
| X3 | Farming Experience | −0.0545 | −0.1169 | 0.0437 (X1) | 0.0100 (X5) |
| X4 | Family Size | −0.1257 | −0.1657 | 0.0487 (X5) | 0.0054 (X1) |
| X5 | Family Type | 0.0766 | −0.3125 | 0.0058 (X1) | 0.0030 (X14) |
| X6 | Occupation | 0.0523 | 0.0104 | 0.0803 (X9) | 0.0187 (X11) |
| X7 | Total Landholding | −0.1219 | 0.1247 | 0.1311 (X9) | 0.0105 (X2) |
| X8 | Livestock | −0.0169 | −0.0025 | 0.0717 (X9) | 0.0151 (X6) |
| X9 | Annual Income | 0.2489 | 0.0668 | 0.0556 (X12) | 0.0256 (X15) |
| X10 | Social Participation | −0.0516 | 0.0734 | 0.0940 (X12) | 0.0505 (X11) |
| X11 | Mass Media | 0.1767 | 0.1173 | 0.0773 (X12) | 0.0316 (X9) |
| X12 | Extension Participation | 0.3041 | 0.2056 | 0.0874 (X15) | 0.0455 (X9) |
| X13 | Innovative proneness | 0.1322 | 0.1234 | 0.0385 (X12) | 0.0257 (X4) |
| X14 | Achievement Motivation | −0.0557 | 0.2524 | 0.1171 (X12) | 0.0684 (X15) |
| X15 | Risk Orientation | 0.2755 | 0.1697 | 0.0964 (X12) | 0.0359 (X16) |
| X16 | Scientific Orientation | 0.0635 | 0.3090 | 0.1559 (X15) | 0.1371 (X12) |

these constraints, along with providing necessary support and resources, can encourage more farmers to adopt climate-smart agriculture practices.

5. Stakeholder involvement, support from development organizations and line departments, and the availability of production inputs are crucial factors for promoting the adoption

TABLE 9 Path effect of a profile of the farmers on the adoption of CSA technologies ($n$ = 240).

| Sr. No. | Factors | Total Direct effect | Total Indirect effect | Substantial effect | |
|---|---|---|---|---|---|
| | | | | 1 | 2 |
| X1 | Age | 0.0047 | −0.1871 | 0.0063 (X7) | 0.0043 (X5) |
| X2 | Education | 0.0819 | 0.1726 | 0.0583 (X9) | 0.0417 (X4) |
| X3 | Farming Experience | 0.0045 | −0.1799 | 0.0072 (X5) | 0.0028 (X1) |
| X4 | Family Size | −0.2105 | −0.0891 | 0.0348 (X5) | 0.0091 (X10) |
| X5 | Family Type | 0.0548 | −0.2553 | 0.0103 (X10) | 0.0035 (X8) |
| X6 | Occupation | 0.0778 | 0.1040 | 0.1204 (X9) | 0.0121 (X11) |
| X7 | Total Landholding | −0.1054 | 0.2218 | 0.1965 (X9) | 0.0097 (X14) |
| X8 | Livestock | 0.0243 | 0.1058 | 0.1075 (X9) | 0.0225 (X6) |
| X9 | Annual Income | 0.3730 | 0.0774 | 0.0438 (X12) | 0.0251 (X6) |
| X10 | Social Participation | 0.0622 | 0.1172 | 0.0741 (X12) | 0.0397 (X9) |
| X11 | Mass Media | 0.1143 | 0.1982 | 0.0610 (X12) | 0.0474 (X9) |
| X12 | Extension Participation | 0.2398 | 0.2241 | 0.0682 (X9) | 0.0452 (X4) |
| X13 | Innovative proneness | 0.0880 | 0.1334 | 0.0431 (X4) | 0.0375 (X9) |
| X14 | Achievement Motivation | 0.0999 | 0.1506 | 0.0924 (X12) | 0.0204 (X11) |
| X15 | Risk Orientation | 0.0226 | 0.1611 | 0.0760 (X12) | 0.0346 (X9) |
| X16 | Scientific Orientation | 0.0273 | 0.1916 | 0.1081 (X12) | 0.0420 (X14) |

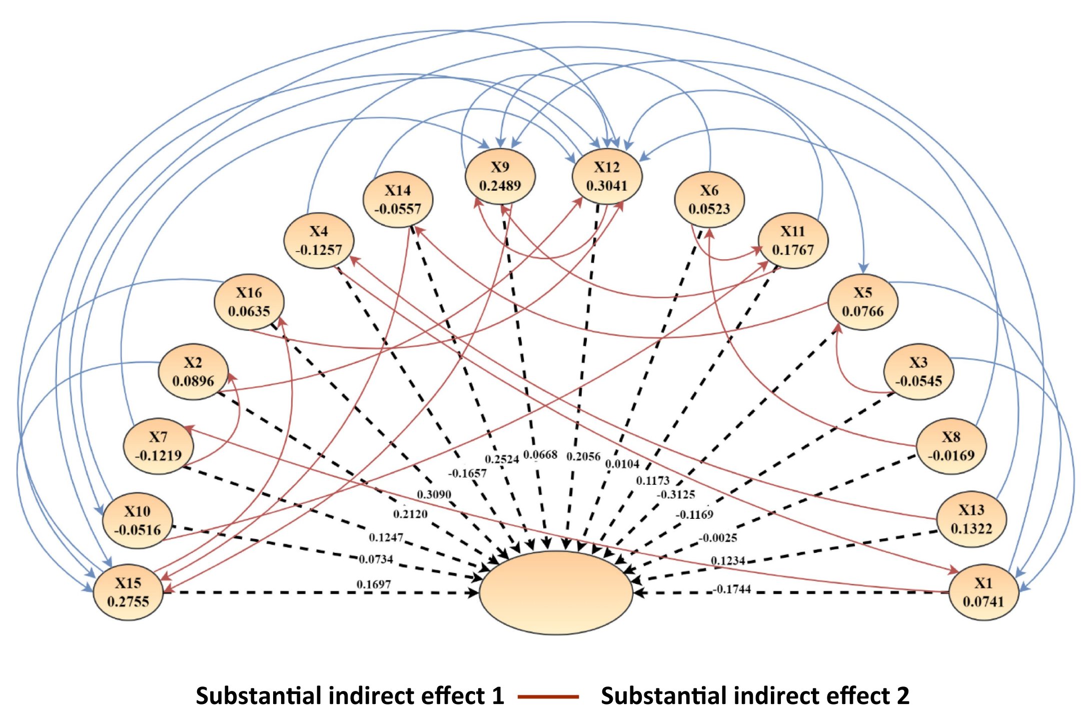


FIGURE 3
Direct and Indirect effect of characteristics of the farmers on awareness about CSA technologies.

of CSA technologies. Farmers emphasize the importance of financial support, field demonstrations, and access to improved crop variety seeds to facilitate the adoption process.

6. Principal Component Analysis (PCA) provides insights into the relationship between various factors and the overall variation in awareness and adoption of CSA technologies. Psychological components and economic factors are identified as significant contributors to farmers' awareness and adoption levels, respectively.

These conclusions highlight the current state of awareness and adoption of climate-smart agriculture technologies among farmers,

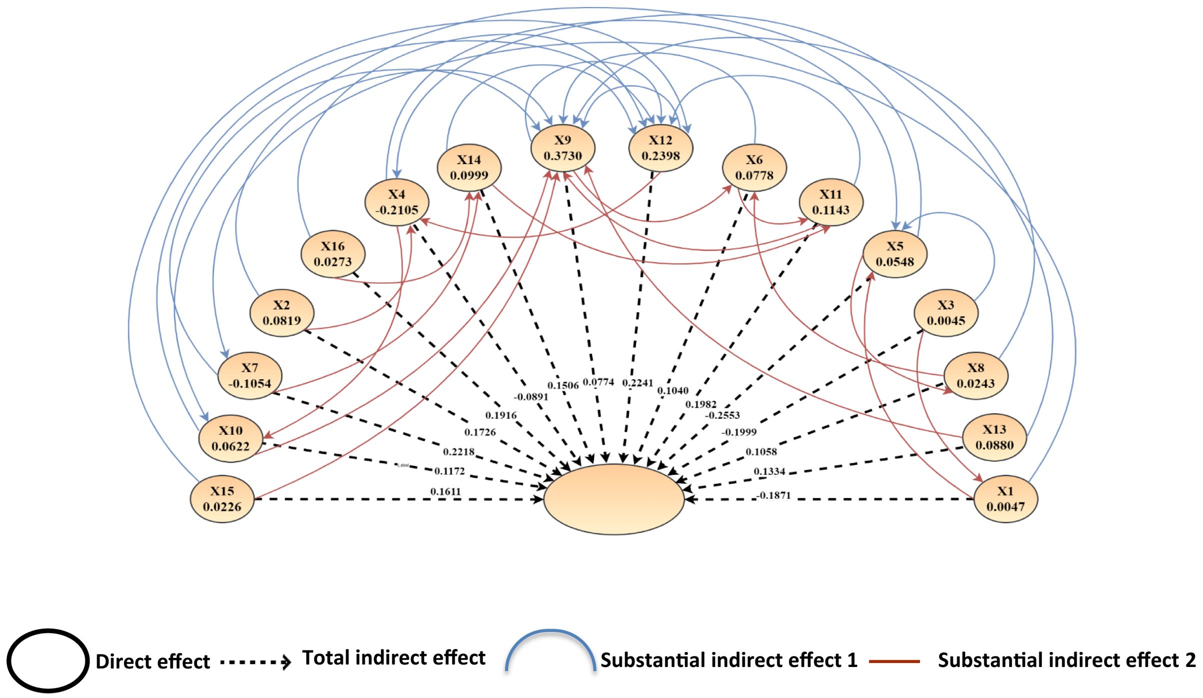


FIGURE 4
Direct and Indirect effect of characteristics of the farmers on adoption of CSA technologies.

TABLE 10 Challenges faced by the farmers in the adoption of CSAT ($n = 240$).

| Sl. No. | Farmers Constraints | Frequency | Percentage | Rank |
|---|---|---|---|---|
| 1. | High costs of inputs | 205 | 85.42 | I |
| 2. | Lack of sufficient knowledge about the CSAT | 181 | 75.42 | II |
| 3. | Migration of youth | 180 | 75.00 | III |
| 4. | Lack of awareness about climate change issues | 168 | 70.00 | IV |
| 5. | Lack of farmers-friendly CSA technologies | 167 | 69.58 | V |
| 6. | Lack of legal and policy frameworks of government | 166 | 69.17 | VI |
| 7. | Uncertain returns | 164 | 68.33 | VII |
| 8. | No extension activities about CSA Technologies | 164 | 68.33 | VIII |
| 9. | Lack of knowledge about adaptive practices of CSA | 158 | 65.83 | IX |
| 10. | Poor information dissemination about the technologies | 157 | 65.42 | X |
| 11. | Non-availability of labour for the adoption of CSA technologies | 156 | 65.00 | XI |
| 12. | Small landholding | 155 | 64.58 | XII |
| 13. | Lack of access to credit | 150 | 62.50 | XIII |
| 14. | No subsidies on planting materials | 149 | 62.08 | XIV |
| 15. | Non-availability of inputs on time | 148 | 61.67 | XV |
| 16. | Limited marketing access | 143 | 59.58 | XVI |
| 17. | Inadequate assistance from national and local authorities with climate-related issues | 135 | 56.25 | XVII |
| 18. | Lack of improved communication facility | 130 | 54.17 | XVIII |
| 19. | Lack of farmers' organisation | 119 | 49.58 | XIX |
| 20. | Lack of necessary transportation facilities | 113 | 47.08 | XX |
| 21. | Poor supply of uniform electricity | 95 | 39.58 | XXI |
| 22. | Lack of irrigation facilities | 94 | 39.17 | XXII |

**TABLE 11** Farmers' suggestions for greater adoption of CSAT ($n = 240$).

| Sl No | Farmers suggestions | Frequency | Percentage | Rank |
|---|---|---|---|---|
| 1. | Farmers' participation in technological development | 232 | 96.67 | I |
| 2. | The development organisations and line departments should make sure that production inputs are available throughout the cropping season | 209 | 87.08 | II |
| 3. | Arranging visits to successful fields | 201 | 83.75 | III |
| 4. | Arranging financial support for the adoption and purchase of inputs | 195 | 81.25 | IV |
| 5. | Demonstration of CSA technologies in villages | 194 | 80.83 | V |
| 6. | Availability of improved crop variety seeds in the village | 185 | 77.08 | VI |
| 7. | Training on Climate Smart Agricultural technologies | 181 | 75.42 | VII |
| 8. | Supply and availability of inputs at a cheaper price. | 179 | 74.58 | VIII |
| 9. | Insurance must be provided for all crops. | 178 | 74.17 | IX |
| 10. | Providing financial support for soil nutrient enrichment | 150 | 62.5 | X |
| 11. | Showing films on Climate Smart Agricultural technologies | 147 | 61.25 | XI |
| 12. | Group credit access | 134 | 55.83 | XII |
| 13. | Distribution of literature on Climate Smart Agricultural technologies | 112 | 46.67 | XIII |

the factors influencing their decisions, and the constraints they face. By addressing these findings, policymakers and agricultural stakeholders can develop targeted interventions and support mechanisms to promote the widespread adoption of climate-smart agriculture practices.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## Author contributions

The conceptualisation and methodology are contributions from VH and TP. VH contributed software, validation, data collection, formal analysis, and written an original draft. TP assisted in review and editing. All authors contributed to the article and approved the submitted version.

## Funding

This research was funded by Anand Agricultural University, Anand, Gujarat.

## Acknowledgments

The authors gratefully acknowledge technical and financial support from the Anand Agricultural University, Anand, Gujarat. The authors are very much thankful to the Gujarat state of India farmers for their cooperation during the survey work.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## References

Abegunde, V. O., Sibanda, M., and Obi, A. (2019). Determinants of the adoption of climate-smart agricultural practices by small-scale farming households in king cetshwayo district municipality, South Africa. *Sustainability* 12:195. doi: 10.3390/su12010195

Abera, W., Assen, M., and Budds, J. (2020). Determinants of agricultural land management practices among smallholder farmers in the Wanka watershed, northwestern highlands of Ethiopia. *Land Use Policy* 99:104841. doi: 10.1016/j.landusepol.2020.104841

Aryal, J. P., Rahut, D. B., Maharjan, S., and Erenstein, O. (2018). Factors affecting the adoption of multiple climate-smart agricultural practices in the indo-Gangetic Plains of India. *Nat. Res. Forum* 42, 141–158. doi: 10.1111/1477-8947.12152

Aryal, J. P., Sapkota, T. E. K. B., Jat, M. L., and Bishnoi, D. K. (2015). On-farm economic and environmental impact of zero-tillage wheat: a case of north-West India. *Exp. Agric.* 51, 1–16. doi: 10.1017/S001447971400012X

Aryal, J. P., Sapkota, T. B., Khurana, R., Khatri-Chhetri, A., Rahut, D. B., and Jat, M. L. (2020). Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environ. Dev. Sustain.* 22, 5045–5075. doi: 10.1007/s10668-019-00414-4

Ayat, U., Shahab, E. S., and Harald, K. (2022). Determinants of farmers' awareness and adoption of extension recommended wheat varieties in the Rainfed areas of Pakistan. *Sustainability* 14:3194. doi: 10.3390/su14063194

Belay, A., Recha, J. W., Woldeamanuel, T., and Morton, J. F. (2017). Smallholder farmers' adaptation to climate change and determinants of their adaptation decisions in the central Rift Valley of Ethiopia. *Agric. Food Secur.* 6, 1–13. doi: 10.1186/s40066-017-0100-1

Burke, M., Hsiang, S. M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature* 527, 235–239. doi: 10.1038/nature15725

Chand, R., Raju, S. S., and Reddy, A. A. (2015). Assessing performance of pulses and competing crops based on market prices and natural resource valuation. *J. Food Legumes* 28, 335–340.

Chandio, A. A., and Yuanshend, J. (2018). Determinants of adoption of improved Rice varieties in. *Rice Sci.* 25, 103–110. doi: 10.1016/j.rsci.2017.10.003

Djufry, F., Suci, W., and Renato, V. (2022). Climate smart agriculture implementation on coffee smallholders in Indonesia and strategy to accelerate. *Land* 11:1112. doi: 10.3390/land11071112

FAO (2009). High level expert forum - how to feed the world in 2050. Office of the Director, agricultural development economics division. Economic and social development department. Viale delle Terme di Caracalla, 00153 Rome, Italy.

FAO (2011). Climate change, water and food security. Rome, Italy: Sales and Marketing Group, Information Division, Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/3/i2096e/i2096e.pdf

FAO (2015a). Climate change and food security: Risks and responses. Rome, Italy: Sales and Marketing Group, Information Division, Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/3/i5188e/I5188E.pdf

FAO (2015b). The economic lives of smallholder farmers. An analysis based on household data from nine countries. Rome, Italy: Sales and Marketing Group, Information Division, Food and Agriculture Organization of the United Nations.

FAO (2017). Climate-smart crop production. Rome, Italy: Sales and Marketing Group, Information Division, Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/climate-smart-agriculture-sourcebook/production-resources/module-b1-crops/b1-overview/en/

Feliciano, D. (2019). A review on the contribution of crop diversification to sustainable development goal 1 "no poverty" in different world regions. *Sustain. Dev.* 27, 795–808. doi: 10.1002/sd.1923

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F. (2010). Food security: The challenge of feeding 9 billion people. *Science* 327, 812–818. doi: 10.1126/science.1185383

Gustafson, D., Asseng, S., Kruse, J., Thoma, G., Guan, K., Hoogenboom, G., et al. (2021). Supply chains for processed potato and tomato products in the United States will have enhanced resilience with planting adaptation strategies. *Nat. Food* 2, 862–872. doi: 10.1038/s43016-021-00383-w

Hariharan, V. K., Mittal, S., Rai, M., Agarwal, T., Kalvaniya, K. C., Stirling, C. M., et al. (2020). Does climate-Smart Village approach influence gender equality in farming households? A case of two contrasting ecologies in India. *Clim. Chang.* 158, 77–90. doi: 10.1007/s10584-018-2321-0

Hatfield, J. L., Antle, J., Garrett, K. A., Izaurralde, R. C., Mader, T., Marshall, E., et al. (2020). Indicators of climate change in agricultural systems. *Clim. Chang.* 163, 1719–1732. doi: 10.1007/s10584-018-2222-2

Headey, D., Dereje, M., and Taffesse, A. S. (2014). Land constraints and agricultural intensification in Ethiopia: a village-level analysis of high-potential areas. *Food Policy* 48, 129–141. doi: 10.1016/j.foodpol.2014.01.008

Hebbsale Mallappa, V. K., and Shivamurthy, M. (2021). Factor influencing fishery-based farmers' perception and their response to climate-induced crisis management. *Environ. Dev. Sustain.* 23, 11766–11791. doi: 10.1007/s10668-020-01141-x

Holden, S. T., Fisher, M., Katengeza, S. P., and Thierfelder, C. (2018). Can lead farmers reveal the adoption potential of conservation agriculture? The case of Malawi. *Land Use Policy* 76, 113–123. doi: 10.1016/j.landusepol.2018.04.048

IPCC (2012). Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change [field, C.B., V. Barros, T.F. stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge university press, Cambridge, UK, and New York, NY, USA, 582 pp.

Jirata, M., Grey, S., and Kilawe, E. (2016). Ethiopia climate-smart agriculture scoping study; FAO: Addis Ababa, Ethiopia, 2016.

Khatri-Chhetri, A., Aryal, J. P., Sapkota, T. B., and Khurana, R. (2016). Economic benefits of climate-smart agricultural practices to smallholder farmers in the indo-Gangetic Plains of India. *Curr. Sci.* 110, 1251–1256.

Kifle, T., Ayal, D. Y., and Mulugeta, M. (2022). Factors influencing farmers adoption of climate smart agriculture to respond climate variability in Siyadebrina Wayu District, Central highland of Ethiopia. *Clim. Serv.* 26:100290. doi: 10.1016/j.cliser.2022.100290

Kukal, M. S., and Irmak, S. (2018). Climate-driven crop yield and yield variability and climate change impacts on the U.S. great plains agricultural production. *Sci. Rep.* 8:3450. doi: 10.1038/s41598-018-21848-2

Kurgat, B. K., Lamanna, C., Kimaro, A., Namoi, N., Manda, L., and Rosenstock, T. S. (2020). Adoption of climate-smart agriculture Technologies in Tanzania. *Front. Sustain. Food Syst.* 4:55. doi: 10.3389/fsufs.2020.00055

Lobell, D. B., and Gourdji, S. M. (2012). The influence of climate change on global crop productivity. *Plant Physiol.* 160, 1686–1697.

Long, T. B., Blok, V., and Coninx, I. (2016). Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy. *J. Clean. Prod.* 112, 9–21. doi: 10.1016/j.jclepro.2015.06.044

Lulia, I. (2012). Climate-smart agriculture produces more food sustainably. International Atomic Energy Agency (IAEA), Division of Public Information. Vienna, Austria: Vienna International Centre. Available at: https://www.iaea.org/newscenter/news/climate-smart-agriculture-produces-more-food-sustainably

Malhi, G. S., Kaur, M., and Kaushik, P. (2021). Impact of climate change on agriculture and its mitigation strategies: a review. *Sustainability* 13:1318. doi: 10.3390/su13031318

Marenya, P. P., and Barrett, C. B. (2007). Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya. *Food Policy* 32, 515–536. doi: 10.1016/j.foodpol.2006.10.002

McNamara, K. T., Wetzstein, M. E., and Douce, G. K. (1991). Factors affecting peanut producer adoption of integrated pest management. *Rev. Agric. Econ.* 13, 129–139. doi: 10.2307/1349563

Mehta, Avantika (2019). Drought-Hit Gujarat Has Water For Factories, But Not For Farmers. New Delhi, India: Indiaspend. Available at: https://www.indiaspend.com/drought-hit-gujarat-has-water-for-factories-but-not-for-farmers/

Miheretu, B. A., and Yimer, A. A. (2017). Determinants of farmers' adoption of land management practices in Gelana sub-watershed of northern highlands of Ethiopia. *Ecol. Process.* 6:19. doi: 10.1186/s13717-017-0085-5

Ministry of Agriculture and Farmers' Welfare (2015). Doubling farmers' income-volume XI. Empowering the farmers through extension. Department of Agriculture, cooperation and farmers' welfare, Ministry of Agriculture & farmers' welfare, Government of India. Available at: https://agricoop.gov.in/sites/default/files/DFI%20Volume%2011.pdf

Mota, A. A., Lachore, S. T., and Handiso, Y. H. (2019). Assessment of food insecurity and its determinants in the rural households in Damot Gale Woreda, Wolaita zone, sothern Ethiopia. *Agric. Food Secur.* 8, 1–11.

Muhammad, A. I., and Marie, J. (2021). Attitudes to climate change adaptation in agriculture – a case study of Öland, Sweden. *J. Rural. Stud.* 86, 1–15. doi: 10.1016/j.jrurstud.2021.05.024

Mujeyi, A., Mudhara, M., and Mutenje, M. J. (2019). Adoption determinants of multiple climate smart agricultural technologies in Zimbabwe: considerations for scaling-up and out. *Afr. J. Sci. Technol. Innov. Dev.* 12, 1–12.

Mujeyi, A., Mudhara, M., and Mutenje, M. (2021). The impact of climate smart agriculture on household welfare in smallholder integrated crop–livestock farming systems: evidence from Zimbabwe. *Agric. Food Secur.* 10:4. doi: 10.1186/s40066-020-00277-3

Murage, A. W., Midega, C. A. O., Pittchar, J. O., Pickett, J. A., and Khan, Z. R. (2015). Determinants of adoption of climate-smart push-pull technology for enhanced food security through integrated pest management in eastern Africa. *Food Sec.* 7, 709–724. doi: 10.1007/s12571-015-0454-9

Musafiri, C. M., Kiboi, M., Macharia, J., Ng'etich, O. K., Kosgei, D. K., Mulianga, B., et al. (2021). Adoption of climate-smart agricultural practices among smallholder farmers in Western Kenya: do socioeconomic, institutional, and biophysical factors matter? *Heliyon* 8:e08677. doi: 10.1016/j.heliyon.2021.e0867

Mwungu, C. M., Mwongera, C., Shikuku, K. M., Acosta, M., and Läderach, P. (2018). "Determinants of adoption of climate-smart agriculture Technologies at Farm Plot Level: an assessment from southern Tanzania" in *Handbook of climate change resilience*. ed. W. L. Filho (Springer International Publishing), 1–15.

Negera, M., Alemu, T., Hagos, F., and Haileslassie, A. (2022). Determinants of adoption of climate smart agricultural practices among farmers in bale-eco region, Ethiopia. *Heliyon* 8:e09824. doi: 10.1016/j.heliyon.2022.e09824

Nyasimi, M., Kimeli, P., Sayula, G., Radeny, M., Kinyangi, J., and Mungai, C. (2017). Adoption and dissemination pathways for climate-smart agriculture technologies and practices for climate-resilient livelihoods in lushoto, Northeast tanzania. *Climate* 5, 2–22. doi: 10.3390/cli5030063

Ogato, G. S. (2014). Biophysical, socio-economic, and institutional constraints for production and flow of cereals in Ethiopia. *AJHE* 3, 51–71.

Ouédraogo, M., Houessionon, P., Zougmoré, R. B., and Partey, S. T. (2019). Uptake of climate-smart agricultural technologies and practices: actual and potential adoption rates in the climate-smart village site of Mali. *Sustainability* 11:4710. doi: 10.3390/su11174710

Parajuli, R., Thoma, G., and Matlock, M. D. (2019). Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: a review. *Sci. Total Environ.* 650, 2863–2879. doi: 10.1016/j.scitotenv.2018.10.019

Patel, H. R., Lunagaria, M. M., Karande, B. I., Yadav, S. B., Shah, A. V., Sood, V. K., et al. (2015). Climate change and its impact on major crops in Gujarat. *J. Agrometeorol.* 17, 190–193. doi: 10.54386/jam.v17i2.1003

Pathak, T. B., Maskey, M. L., Dahlberg, J. A., Kearns, F., Bali, K. M., and Zaccaria, D. (2018). Climate change trends and impacts on California agriculture: a detailed review. *J. Agron.* 8:25. doi: 10.3390/agronomy8030025

Patle, G. T. (2021). Climate smart water saving techniques for mitigation of climate change impacts in hill agriculture. Available at: https://www.thesangaiexpress.com/Encyc/2021/12/7/GT-PatleClimate-change-expected-to-intensify-the-demands-of-water-use-in-agriculture-as-climate-is.html

Petronilla, M., David, H., and Lyn, P. (2016). Factors contributing to adoption and use of information and communication technologies within research collaborations in Kenya. *Inf. Technol. Dev.* 22, 84–100. doi: 10.1080/02681102.2015.1121856

Philip, T., and Leslie, L. (2014). How does climate change Alter agricultural strategies to support food security? International food policy research institute (IFPRI). Washington, DC.

Ravi, S. P., and Ridhima, S. (2019). Implementing climate change adaptation: lessons from India's national adaptation fund on climate change (NAFCC). *Clim. Pol.* 19, 354–366. doi: 10.1080/14693062.2018.1515061

Raza, A., Razzaq, A., Mehmood, S. S., Zou, X., Zhang, X., Lv, Y., et al. (2019). Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. *Plants* 8:34. doi: 10.3390/plants8020034

Salerno, J., Stevens, F. R., Gaughan, A. E., Hilton, T., Bailey, K., Bowles, T., et al. (2021). Wildlife impacts and changing climate pose compounding threats to human food security. *Curr. Biol.* 31, 5077–5085.e6. doi: 10.1016/j.cub.2021.08.074

Scott, S. D., Plotnikoff, R. C., Karunamuni, N., Bize, R., and Rodgers, W. (2008). Factors influencing the adoption of an innovation: an examination of the uptake of the Canadian heart health kit (HHK). *Implement. Sci.* 3:41. doi: 10.1186/1748-5908-3-41

Shaw, R., Prabhakar, S. V. R. K., and Fujieda, A. (2005). *Community level climate change adaptation and policy issues: A case study from Gujarat*, India. Graduate School of Global Environmental Studies. Kyoto University, Japan, p 59

Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H. O., Roberts, D. C., et al. (2019). *An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*; IPCC: Geneva, Switzerland, 2019.

Sivabalan, K. C., and Nithila, S. (2018). Farmers' capacity strengthening and climate advisory services for combating climate change in India. *J. Pharmacogn. Phytochem.* 7, 179–182.

Sivakumar, M. V. K., and Stefanski, R. (2010). "Climate change in South Asia" in *Climate change and food security in South Asia*. eds. R. Lal, M. Sivakumar, S. Faiz, A. Mustafizur Rahman and K. Islam (Dordrecht: Springer)

Smith, P., Bustamante, M., Ahammad, H. H., Clark, H., Dong, H., Elsiddig, E. A., et al. (2014). "Agriculture, forestry and other land use (AFOLU)" in *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*. eds. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner and K. Seybothet al. (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press).

Tama, R. A. Z., Ying, L., Yu, M., Hoque, M. M., Adnan, K. M., and Sarker, S. A. (2021). Assessing farmers' intention towards conservation agriculture by using the extended theory of planned behavior. *J. Environ. Manag.* 280:111654. doi: 10.1016/j.jenvman.2020.111654

Tesfaye, K., Kassie, M., Cairns, J., Michael, M., Stirling, C., Tsedeke Abate, M., et al. (2017a). "Potential for scaling up climate smart agricultural practices: examples from sub-saharan africa" in *Climate change adaptation in Africa: Fostering resilience and capacity to adapt*. eds. W. Filho, B. Simane, J. Kalungu, M. Wuta, P. Munishi and K. Musiyiwa (Cham, AG: Springer International Publishing), 185–203.

Tesfaye, K., Zaidi, P., Gbegbelegbe, S., Boeber, C., Getaneh, F., Seetharam, K., et al. (2017b). Climate change impacts and potential benefits of heat-tolerant maize in South Asia. *Theor. Appl. Climatol.* 130, 959–970. doi: 10.1007/s00704-016-1931-6

Thomas, W. H. (2011). The global supply and demand for agricultural land in 2050: a perfect storm in the making? *Am. J. Agric. Econ.* 93, 259–275. doi: 10.1093/ajae/aaq189

Tiwari, A., Kesarwani, K., Sharma, A., Ghosh, T., Bisht, N., and Punetha, S. (2022). Drought stress in millets and its response mechanism. IntechOpen.

Tran, D., and Goto, D. (2019). Impacts of sustainability certification on farm income: evidence from small-scale specialty green tea farmers in Vietnam. *Food Policy* 83, 70–82. doi: 10.1016/j.foodpol.2018.11.006

Tsige, M., Synnevåg, G., and Aune, J. B. (2020). Gendered constraints for adopting climate-smart agriculture amongst smallholder Ethiopian women farmers. *Sci. Afr.* 7:e00250

Vågsholm, I., Arzoomand, N. S., and Boqvist, S. (2020). Food security, safety, and sustainability—getting the trade-offs right. *Front. Sustain. Food Syst.* 4:16. doi: 10.3389/fsufs.2020.00016

Vinaya Kumar, H. M., Shivamurthy, M., Govinda Gowda, V., and Biradar, G. S. (2017). Assessing decision-making and economic performance of farmers to manage climate-induced crisis in coastal Karnataka (India). *Clim. Chang.* 142, 143–153. doi: 10.1007/s10584-017-1928-x

Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., et al. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Sci. Total Environ.* 733, 137782–137718. doi: 10.1016/j.scitotenv.2020.137782

World Bank (2020). The adaptation principles: 6 ways to build resilience to climate change. Available at: https://www.worldbank.org/en/news/feature/2020/11/17/the-adaptation-principles-6-ways-to-build-resilience-to-climate-change

World Bank (2021). Climate-Smart Agriculture. Available at: https://www.worldbank.org/en/topic/climate-smart-agriculture

Wright, S. (1921). Correlation and Causation. *J. Agric. Res.* 20, 557–585.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, L., et al. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci. U. S. A.* 114, 9326–9331. doi: 10.1073/pnas.1701762114

Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 15 August 2023
DOI 10.3389/fsufs.2023.1222455

OPEN ACCESS

EDITED BY
Subhasis Mandal,
National Dairy Research Institute (ICAR), India

REVIEWED BY
László Vasa,
Széchenyi István University, Hungary
Raquel Ajates,
Universidad Nacional de Educación a Distancia (UNED), Spain

*CORRESPONDENCE
Mingwei Yang
✉ 2020651906@email.ctbu.edu.cn

RECEIVED 14 May 2023
ACCEPTED 03 August 2023
PUBLISHED 15 August 2023

CITATION
Liu J, Yang M and Zhang Z (2023) Can rural cooperatives reduce poverty vulnerability of smallholder households? Evidence from rural Western China.
*Front. Sustain. Food Syst.* 7:1222455.
doi: 10.3389/fsufs.2023.1222455

# Can rural cooperatives reduce poverty vulnerability of smallholder households? Evidence from rural Western China

Jianzhong Liu[1], Mingwei Yang[2]* and Zhiyong Zhang[2]

[1]School of Marxism Studies, Hunan International Economics University, Changsha, China, [2]Research Center for Economy of Upper Reaches of the Yangtse River, Chongqing Technology and Business University, Chongqing, China, [3]Qinghai University Library, Qinghai University, Xining, Qinghai, China

**Introduction:** Poverty eradication is one of the global challenges, and rural cooperatives provide an effective path to address smallholder households' poverty. However, the effect of poverty reduction can show heterogeneity depending on the economic capital, human capital, and social capital of households.

**Methods:** Based on comprehensive research data on the poverty status of 1,622 smallholder households in four provinces in the less developed regions of western China, using OLS and PSM models, this paper empirically analyzes the impact and heterogeneous characteristics of rural cooperatives on the poverty vulnerability of smallholder households.

**Results/Discussion:** The results show that rural cooperatives have a significant dampening effect on the poverty vulnerability of smallholder farmers, and the findings hold true after robustness tests using multiple methods. The impact of rural cooperatives on the poverty vulnerability of farming households differed significantly across smallholder households with different characteristics. Specifically, participation in cooperatives had a more pronounced effect on reducing poverty vulnerability among non-poor, higher human capital and higher income farm households compared to poor, lower human capital and lower income farm households. The results of the study can provide a useful reference for policy-making on rural mutual assistance and poverty reduction among farmers.

KEYWORDS

**rural cooperatives, poverty vulnerability, smallholder households, rural mutual assistance, poverty alleviation**

## 1. Introduction

The alleviation and elimination of poverty is a common goal of human development and a worldwide challenge (Wang et al., 2022). In 2020, the Chinese government announced that it had achieved the goal of eradicating absolute poverty, which is an important milestone in the history of the fight against poverty in humanity. However, smallholder households in rural China, especially in the western region, are still at serious risk of poverty. On the one hand, China's poverty standard is only roughly equivalent to the World Bank's extreme poverty line,[1] if the low-middle poverty line and the high-middle poverty line are applied, China still has a large number of low-income people; On the other hand, many families are at risk of returning to poverty. Nearly 2 million people who have escaped poverty are at risk of returning to poverty, and nearly 3 million of the marginal population are at risk of becoming poor (Xu and Li, 2023; Zhang et al., 2023). Reducing the risk of poverty among low-income groups is therefore the central task in China's rural revitalization strategy.

Between 1979 and 1984, China's land system underwent a dramatic shift from collective farming based on production teams (equivalent to villages) to a family-based system of responsibility under the household joint production contract. The central feature of this system is the decentralization of the management of arable land from collective to family management. Under China's family contract responsibility policy, farmers' motivation to produce gets a boost. However, it also brings with it the difficulty of agricultural decentralization. Most farming households have a small landholding, with an average household size of less than 0.67 hectares (Yang et al., 2023). The 'small scale' nature of agricultural production activities makes it necessary for smallholder farmers to allocate their resources between rural and urban areas in order to obtain sufficient income to meet household consumption expenditure. This leads mainly to three distinct vulnerabilities of smallholder households (Zhang et al., 2016). How effective is education in fighting poverty? Researchers are still divided on this question. An analysis of Pakistani households found that educational attainment was negatively associated with the incidence of poverty among farming households, and that access to higher levels of education reduced the likelihood of farming households falling into poverty (Jia and Xu, 2021). However, some studies have found that some of the educational reform in Uganda designed for low income groups did not achieve poverty level reductions (Saz-Gil et al., 2021). Finally, social networks are an important part of social capital, enhances action by playing a role in instrumental and expressive action, with resources embedded in social networks. By embedding social capital in external social networks, cooperatives build close and strong relationships with other network actors and gain greater access to knowledge and information exchange to improve the efficiency of resource acquisition. Social capital plays a role in signaling, monitoring, steering, reducing inter-organizational transaction costs, 'collateral' substitution and risk reduction, and by reducing the level of mistrust between individuals, it improves collective cohesion and promotes cooperation (Person et al., 2017; Ajates, 2021). Small farmers, mainly left-behind farmers, have been integrated into the traditional social life of the countryside, where social relations are more closed (Liang et al., 2015; Ma and Abdulai, 2017).

For most smallholder farmers, it is often difficult to effectively enhance their capacity for autonomous development simply by relying on their own efforts. Farmers' cooperatives (hereafter referred to as cooperatives), as 'self-organizations' of farmers, have attracted the attention of many scholars in terms of increasing farmers' incomes and reducing poverty (Deng et al., 2021; Cheng et al., 2022). Some scholars argue that cooperatives should be regarded as an efficient organizational innovation in rural poverty governance because of their ability to fundamentally improve the efficiency of the use of poverty reduction funds and to improve the income, capacity and rights poverty of farm households (Ma and Abdulai, 2017). Cooperatives convey agricultural knowledge while improving the market competitiveness and social adaptability of poor farmers by enhancing their individual capacities, and repairing the capacity deficits of farmers in the new economy (Bacon et al., 2014). The mechanisms inherent in the participation of poor farmers in cooperatives to reduce poverty and increase income are partly the result of the individual empowerment of members through their business, capital and management participation in the cooperative, and this capacity-enhancing effect is greater for middle- and high-income farmers (Bernard et al., 2008; Verhofstadt and Maertens, 2014).

In general, most of the available studies confirm the positive role of cooperatives in reducing poverty and increasing income (Chagwiza et al., 2016; Cafer and Rikoon, 2018; Kumar et al., 2018). Cooperatives have an advantage over scattered smallholder farmers in terms of large-scale farming, use of advanced technologies, coping with market risks and access to policy subsidies, increasing the added value, profitability, labor productivity and employment of farmers engaged in agricultural production (Ito et al., 2012). Co-operatives not only help farmers reduce transaction costs in the procurement of agricultural materials and agricultural production services, but also improve their bargaining power in the sale of agricultural products; they also provide various types of training and activities to help farmers improve their ability to obtain information, express their needs and apply technology, thereby increasing their income (Kumar et al., 2018).

However, some scholars have also found that farmer group differences have a key impact on the poverty-reducing effects of cooperatives. Some cooperatives have evolved into "self-run enterprises" that do not contribute to the development of their members or to the income of farmers as a whole (Bernard and Taffesse, 2012). The natural heterogeneity of smallholder farmers in terms of their initial resource endowments, such as production and management capacity, risk tolerance and household livelihood capital, may lead to "elite capture," resulting in the diversion of poverty alleviation resources and misalignment of project implementation, creating new income inequalities (Beuchelt and Zeller, 2013). Some scholars also argue that small and medium-sized members of cooperatives are prone to "free-riding" behavior, unwilling to pay for the cooperative's public services and enjoy the benefits without contributing much, affecting the efficiency of the organization's operations and distributional equity (Tadesse et al., 2019; Ishak et al., 2020).

The above-mentioned studies provide an important theoretical basis for this paper, but there are still shortcomings: firstly, although scholars have focused on the impact of cooperatives on poverty reduction among farmers, they have not yet reached a unanimous conclusion, and most of them are based on theoretical discussions, lacking qualitative and quantitative studies on the impact of cooperatives on farmers' ability to reduce poverty. Secondly, few scholars have studied the heterogeneous effects of cooperatives on the future poverty reduction capacity of smallholder farmers from the perspective of farmer differentiation, especially the lack of discussion of groups of farmers with different poverty attributes and different human capital endowments.

---

[1] In 2018, the World Bank used less than US$1.90, US$3.20 and US$5.50 per person per day as the extreme, low and medium poverty lines and the upper secondary poverty line.

The main contribution of this paper is that it uses the cooperative empowerment dimension as an entry point to quantify the reduction effect of cooperatives on farmers' poverty vulnerability and the differences in their effects on heterogeneous groups between groups, enriching the research framework on the "multidimensional pro-poorness" of cooperatives by using the Predominant Score Matching (PSM) method. The remainder of the paper is organized as follows: Section 2 proposes a theoretical analysis and four research hypotheses. Section 3 introduces the identification strategy, variables, and data for this study. Section 4 tests four hypotheses and presents the regression results and covers the heterogeneity analysis and robustness testing. Section 5 provides the discussions, conclusions and related policy implications.

## 2. Theoretical analysis and research hypothesis

The main reason for attracting farmers to join a cooperative is the economic return it can bring to them. Attached to the economic function, cooperatives also generate positive externalities by helping farmers to overcome barriers to market access, improve scientific and cultural literacy, increase social capital stock and empower management (Ito et al., 2012; Kumar et al., 2018). They also have positive externalities in terms of helping farmers overcome barriers to market access, improving scientific and cultural literacy, increasing social capital stock and empowering management, which in turn reduce the poverty vulnerability of smallholder farmers (Chagwiza et al., 2016; Zhang et al., 2023).

With the development of the market economy, agricultural markets are becoming more and more mature. For decentralized smallholders, due to their weakness, asymmetric information, high transaction costs and low standardization of production, they face high barriers to market entry and lack sufficient competitiveness and voice in large markets, and are unable to connect effectively with markets (mainly high value-added markets) on their own (Loconto and Simbua, 2012; Richards and Mendez, 2014). Collective action, i.e., the formation of cooperatives, is an effective mechanism to help resolve the conflict between smallholders and large markets and to increase farmers' participation in the market (Beuchelt and Zeller, 2013).

Collective action provides relevant information and services to smallholders, including technical information and services (agricultural extension and research and development), educational services (production skills training, business skills training and general education), etc. It improves the efficiency and management of farmers' access to agricultural technology and also promotes the sustainable and healthy development of the cooperative (Mavimbela et al., 2010; Meador et al., 2016; Tray et al., 2021). The human capital of the farmers is accumulated and the endogenous motivation for development is further stimulated.

In terms of management participation, democratic management and control is the foundation and core principle of the cooperative system. The participation of members in general meetings, councils and supervisory boards, and the full expression of their views and demands, not only helps to safeguard their own property rights and interests and to obtain more residual claims, but also increases trust within the membership, helps to reduce conflicts in decision-making and the cost of control or supervision in management, ensures the smooth implementation of collective decisions, and minimizes opportunistic behavior on the part of cooperative managers (Bender, 1999; Wollni and Zeller, 2007; Ma and Abdulai, 2016). In general, cooperatives are effective in reducing the poverty vulnerability of smallholder farmers through market access, accelerated human (social) capital formation and empowerment of management. On this basis, we propose hypothesis 1.

> *H1*: Cooperatives can reduce the poverty vulnerability of smallholder households.

From the beginning of their development, cooperatives have been characterized by an external market environment embedded in the vertical integration of agriculture and supply chain management (Verhofstadt and Maertens, 2015). Smallholder farmers are at a distinct disadvantage in terms of enjoying the benefits of global value chains due to their low sales volume and limited bargaining power, as well as the fact that smallholder farmers are often severely limited in their participation in markets by human capital and credit. Especially with the increasing trend toward globalization of agricultural markets and the need for higher management skills and logistics techniques to market agricultural products and meet higher standards of food safety certification, the problem of smallholder participation in integrating into global value chains has become more pronounced, and they even face the risk of being marginalized (An et al., 2015; Fan and Garcia, 2018; Ajates, 2020). As far as the internal environment is concerned, with socio-economic development and the expansion of cooperatives, the structure of group membership has stratified and the heterogeneity of members has increased significantly (Mojo et al., 2017). Therefore, when studying the impact of cooperatives on the poverty vulnerability of smallholder farmers, different group characteristic factors should be included in the examination.

In terms of poverty attributes, on the one hand, poor farmers tend to have a strong will to escape poverty, but show vulnerability characteristics such as poor labor skills, sick and disabled members of the family, heavy child-rearing burden and few risk-averse means (Deng et al., 2021). The greater the vulnerability to poverty, the more risk-sensitive and risk-averse they are. They are reluctant to join a cooperative or even if they do join, they are reluctant to invest in shares, thus becoming passive or dormant members. The stratification between poor and non-poor farmers, and the resulting unequal power patterns, may constrain the accumulation of a virtuous cycle of poverty vulnerability reduction among poor farmers (Ma and Abdulai, 2016). On the other hand, from the perspective of cooperatives, although cooperatives are an effective way to reduce poverty through the organic combination of market and government mechanisms, and objectively have a poverty-reducing effect, some cooperatives do not have an obvious motivation to reduce poverty subjectively, let alone a mature concept of poverty alleviation (Grashuis and Su, 2019). Most of the leaders of co-operatives have a philosophy of serving their own economic performance, and their "deliberate care" for the poor tends to be weakened. Based on economic rationality, co-operatives are exclusive toward poor farmers who lack resources and have low development capacity, and tend to favor non-poor groups who are well endowed with large scale operations and dedicated investments in poor areas (Deng et al., 2010). Even when cooperatives open their membership to poor farmers in general, taking care of poor farmers in a unified operation would mean lower returns for non-poor members (Wollni and Zeller, 2007). The more poor farmers a co-operative takes on, the greater the risk it may face of a decline in overall benefits. On this basis, we propose hypothesis 2.

> *H2*: The effect of poverty vulnerability reduction due to cooperative membership is higher on non-poor farming households than in poor farming households.

Poverty is a vague concept, but it has some basic characteristics, namely that it is mainly marked by "lack," which appears as "low income" and "lack of material and services," but in essence is a lack of "means," "capabilities," "rights" and "opportunities." Education levels are closely linked to the ability of smallholder households to escape poverty (Yang et al., 2023). Better-educated farmers tend to have a greater ability to accept new knowledge and new things and to understand and learn, and their rich knowledge base makes them more likely to accept the organizational system, business philosophy and production techniques of the cooperative, which makes it easier for them to join the cooperative (Ito et al., 2012). Moreover, the stronger the ability to accept new knowledge and technology, the clearer the perception of the cooperative's ability to enhance its own development. On this basis, we propose hypothesis 3.

> *H3*: Cooperatives are more effective in reducing the vulnerability to poverty of households with high human capital endowments than those with low human capital endowments.

Institutional norms of rural cooperatives mainly include formal institutional arrangements and informal institutional norms. We have found that rural cooperatives in China tend to be member-based and rely closely on related enterprises. In terms of management, the cooperative has adopted the practice of "two brands and one set of staff" with the enterprise. The day-to-day management, sales and technical guidance of the cooperative are all dependent on the relevant enterprise, with the core members responsible for the management of the enterprise and the ordinary members only involved in the business work. The heterogeneity of the membership structure of cooperatives is shaped by the differentiation of farming households (van Rijsbergen et al., 2016). This heterogeneity is reflected in the distinction between core members and general members of the cooperative. These two types of members have different levels of income and different levels of participation in the cooperative, resulting in different roles and division of labor, which leads to differences in their ability to improve their skills, showing typical asymmetrical characteristics (Valkila and Nygren, 2010). Compared to core members, general members are usually low-income, low-capital participation groups, and such groups often lack the interest and ability to participate in the public affairs of the cooperative, or even the opportunity to do so (Jitmun et al., 2020). They rarely participate in the day-to-day management and supervision of cooperatives, and are mostly limited to basic aspects such as participation in the purchase of agricultural inputs and materials, the sale of agricultural products, and access to specialized technical services and policy concessions. For core members, their material resource endowments are at an advantage, and they hold the majority of shares in the co-operative, control most of the residual control and residual claims, have more say in the daily production and management activities of the co-operative, and can make full use of their resource endowments and effectively spill over, thus becoming the biggest beneficiaries of the development of the co-operative (Shi et al., 2019; Li et al., 2021). On this basis, we propose hypothesis 4.

> *H4*: Cooperatives are more effective in reducing the poverty vulnerability of middle- and high-income households than of low-income households.

Based on the above analysis, the theoretical analysis framework of this paper is shown in Figure 1.

# 3. Materials and methods

## 3.1. Data

The data in this article comes from a comprehensive survey on the status of rural poverty in Southwest China, July–September 2021. The region covers four provinces, Yunnan, Guizhou, Sichuan and Chongqing. Including eight state-defined poor counties (cities) in Fengjie, Wanzhou, Yunyang, Xishui, Puding, Guang'an, Xuyong, and Dongchuan, 136 villages with 12 farmers per village, a total of 1,632 households in the sample. The research sample was selected based on a three-stage sampling: (1) Cluster analysis sampling. The original 592 state-defined poor counties were divided into three categories of overall poverty status, with experts empirically assessing the worst category and selecting sample provinces and counties in the worst category. (2) Probability Proportional Scale Sampling. Sample villages were selected in proportion to the size of the poor population. (3) Random sampling. A sample of 12 farmers was randomly selected in each village to answer the questionnaire. This sample data represents to a large extent the group of farming households that need the most attention in the less developed counties of China, and is representative and typical. Since the focus of this paper is on smallholder households, farmers with average arable land above 0.67 ha are excluded. After data cleaning and elimination of the 10 questionnaires that did not meet the requirements, the actual research population of this paper is 1,622 households.

## 3.2. Method

### 3.2.1. Poverty vulnerability measurement

Poverty vulnerability, which connects risk shocks to the degree of household welfare, is often seen as unobservable, dynamic, and forward-looking, with a focus on poverty generation expectations (Wang et al., 2022). Poverty vulnerability is the probability that a household or individual will fall into poverty or fail to escape from poverty as a result of exposure to uncertainty risk shocks. Poverty vulnerability is calculated as follows.

$$\hat{V}_i = Prob\left(\ln c_i < \ln z \middle| X_i\right) = \Phi\left[\frac{\left(\ln z - X_i\,\hat{\beta}_{FGLS}\right)}{\sqrt{X_i\,\hat{\theta}_{FGLS}}}\right] \quad (1)$$

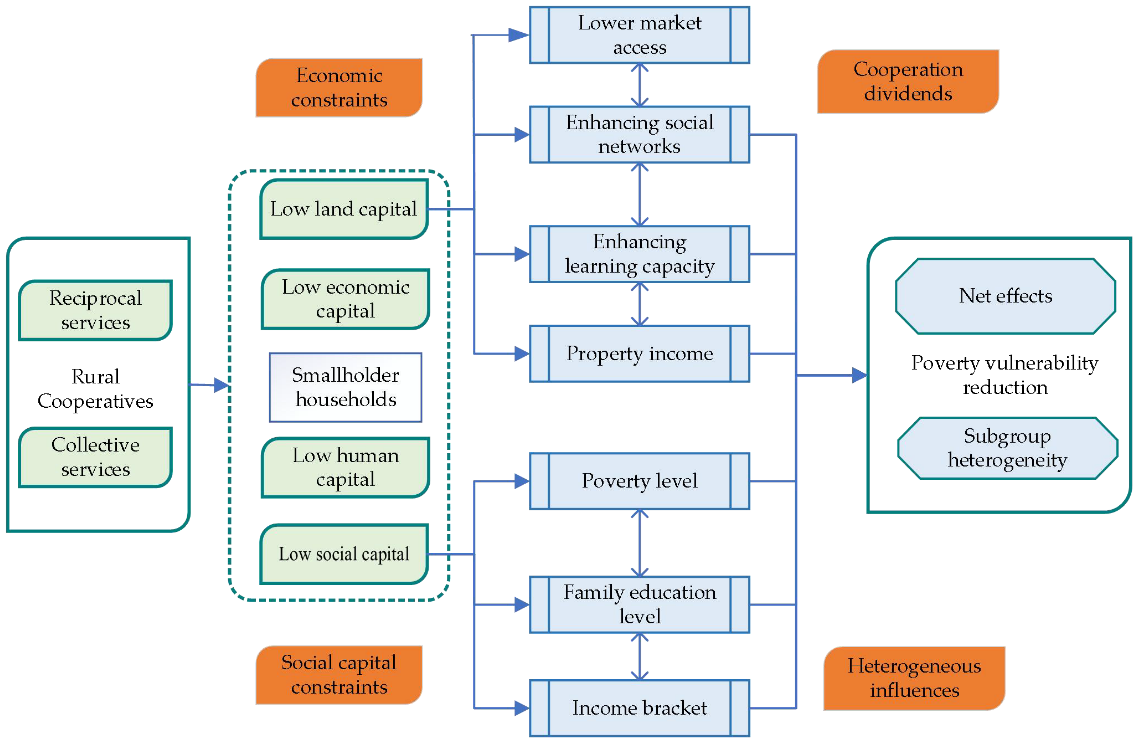


FIGURE 1
A theoretical model of the impact of cooperatives on poverty vulnerability of smallholder households.

Where $\hat{V}_i$ is an estimate of the probability of future poverty for farmer *i*, $c_i$ is the value of *per capita* household consumption, *z* is the delineated poverty line, $\Phi$ is the cumulative distribution function of the normal distribution, $\hat{\beta}_{FGLS}$ and $\hat{\theta}_{FGLS}$ denote the expected value and variance of future household consumption estimated by the FLGS method, respectively. $X_i$ is an observable variable, referring to Wang et al. in their examination of poverty vulnerability by introducing household characteristics variables (including household income, household size, land assets, liabilities, agricultural machinery, etc.) and household head characteristics variables (including age, gender, education, etc.).

### 3.2.2. Econometric model

We constructed an OLS model to examine the impact of cooperatives on poverty vulnerability of smallholder households. The OLS model is set up as in Equation (2):

$$y_i = \alpha + \beta Cooperatives_i + \theta X_i + \varepsilon_i \qquad (2)$$

Among them, $\mathrm{y_i}$ is the poverty vulnerability of smallholder households. $\mathrm{Cooperatives}_i$ represents the participation in a rural cooperative, and $\mathrm{X_i}$ indicates a series of control variables, mainly including family characteristics, village characteristics and head of household Characteristics.

### 3.2.3. Propensity score matching (PSM) model

The propensity score matching method is a counterfactual inference method, the basic idea of which is to find a sample of controls similar to the treatment group to compare their effects, thus effectively solving the endogeneity problem arising from sample selection bias (Yang et al., 2023). Since differences in farmers' initial endowments can directly cause a "selective bias" in their willingness or behavior to join a cooperative, and whether or not to join a cooperative often reflects the ideological tendency of rational farmers to pursue optimal utility, a simple OLS regression of Equation (2), which estimates the capacity-enhancing effect of farmers ignores their own subjective initiative, yields only the conditional expectation effect of the explanatory variables on the explanatory variables, and the results obtained may be biased. The PSM propensity value matching method can effectively solve these problems by finding a control group (uninvolved farmers) with similar characteristics that can simulate the counterfactual state of the treatment group (involved farmers), thus maximizing the elimination of endogeneity problems due to self-selection bias. The specific steps are as follows.

Step 1: we used a logistic model to calculate the conditional probability of a household Participating in rural cooperatives, i.e., the propensity score.

Step 2: based on the propensity scores obtained through three methods: nearest neighbor matching, radius matching and kernel matching, we found a sample of farmers in the control group with propensity scores as similar as possible to those in the treatment group, in order to control and eliminate selectivity errors.

Step 3: PSM model requires that the variables used for matching meet the common support domain assumption and the balance test, and after the sample has been matched and the matching effect has been achieved, we calculate the average treatment effect (ATT). The ATT is calculated as shown below.

$$PS_i = \Pr\left[D_i = 1 | \mathrm{X_i}\right] = \mathrm{E}\left[D_i = 0 | \mathrm{X_i}\right] \tag{3}$$

$$ATT = \frac{1}{N^t} \sum\nolimits_{i \in I^t \cap S} \left\{ Y_i - \sum\nolimits_{j \in I^c \cap S} W_{ij} Y_j \right\} \tag{4}$$

Among them, $N^t$ is the number of samples, $I^t$ is the sample set of the disposal group (Participating in rural cooperatives), $I^c$ is the sample set of the control group (Not Participating in rural cooperatives), $Y_i$ is the observed value of the sample of the disposal group, and $Y_j$ is the sample of the control group. The observations of j, $S$ is the common support domain set, $W_{ij}$ is the matching weight, and ATT is the average disposition effect.

## 3.3. Variables

### 3.3.1. Dependent variables

To forecast household poverty vulnerability, this article uses household *per capita* consumption. One reason for using consumption to define poverty is that income is easily underestimated in micro-surveys, whereas consumption can better reflect the level of family welfare, and the other is that using income as an explanatory variable can easily lead to strong endogenous problems in the measurement model. Regarding the choice of the poverty line, there are primarily two standards of *per capita* daily consumption of US$1.9 and US$3.1 proposed by the World Bank in 2015, which we convert into ¥2,800 and ¥4,570 *per capita* annual consumption based on China's average purchasing power and CPI index (Wang et al., 2022). In the subsequent analysis, we focus on ¥4,570 as the poverty standard line.

### 3.3.2. Independent variables

The core independent variable is whether or not one participates in a cooperative. The ability of cooperatives to bring significant capacity enhancement effects to farmers at different stages of agricultural production depends on whether or not farmers participate in cooperatives. The core explanatory variable is "whether or not the farmer participates in a cooperative," which describes the impact of cooperatives on the poverty vulnerability of smallholder households.

### 3.3.3. Control variables

With reference to existing studies, this paper introduces three types of control variables, namely, variables on individual household head characteristics, variables on household characteristics and variables on village characteristics (Scripcariu et al., 2020; Yin et al., 2020; Ma and Jin, 2022). Household head characteristics include gender, age, and education level; Household characteristics include the number of household labors, net household income *per capita*, level of household poverty, whether there are family members working in the city, total productive assets and annual gift expenses; village characteristics include village transportation conditions and economic status. The descriptive statistical characteristics of the specific variables are shown in Table 1.

# 4. Empirical results

## 4.1. Benchmark regression results

Table 2 reports the results of the benchmark regression of the impact of rural cooperatives on the poverty vulnerability of smallholder households. In Model 1, we only control for the characteristic variables of the household head. In Model 2, we further controlled for household characteristics variables of smallholder farmers. In Model 3, we included household head characteristics, household characteristics and village residence characteristics as control variables. The results show that, controlling for a range of variables, participation in cooperatives can significantly reduce the poverty vulnerability of smallholder farmers. The impact factor is −0.0162, and is significant at the 5% level, which basically supports hypothesis 1 that cooperatives can reduce the poverty vulnerability of smallholder farmers.

The coefficients and signs of the control variables remain consistent with existing studies. The level of education of the household head, the net household income, social capital and the distance from the village to the county have a significant positive impact on the reduction in poverty vulnerability of smallholder farmers. Age of head of household and level of household poverty have a significant negative effect on reduction in poverty vulnerability of smallholder farmers. In addition, the number of laborers and migrant workers also show a negative impact on the reduction of poverty vulnerability, which may be closely related to the demographic disadvantage of smallholder households.

## 4.2. Robustness tests of the PSM model

The benchmark regression results show that joining a rural cooperative can significantly reduce the poverty vulnerability of smallholder farmers. However, there is also a potential problem that OLS regression results are susceptible to sample selection bias, and those factors that are not observed may affect the precision of the estimates. In order to ensure the credibility and robustness of the regression results, we further used the come PSM model to verify the poverty vulnerability reduction effect of cooperatives on farm households. We have selected control variables that were significant in the baseline regression model for the propensity score matching, in order to eliminate the variability of the characteristic variables between the two sample groups.

After propensity score matching, the question of conditional independence between the two sample groups needs to be checked, i.e., there are no significant differences in the characteristics variables between the matched sample groups, except for differences in the poverty vulnerability of the farmers. Table 3 reports the results of the conditional independence hypothesis tests for the explanatory variables before and after PSM matching. After PSM matching, the pseudo $R^2$ decreases from 0.013 before matching to 0.001–0.003 after matching. LR chi2, B-values and mean bias-value have all fallen substantially. All *p* values are greater than 10%. Thus, after matching by the PSM model, we significantly eliminate systematic differences in the distribution of explanatory variables between the treatment and control groups, minimize sample selection bias, and propensity score estimation and sample matching are more successful, significantly weakening estimation bias due to self-selection.

In Table 4, we used five PSM methods to estimate ATT, ATU and ATE for the impact of cooperatives on the poverty vulnerability of smallholder farmers. Among them, ATT represents the average treatment effect of the treatment group; ATU represents the average treatment effect of the control group; ATE is the average treatment effect for the overall sample. The results show that the five matching methods ATT, ATU and ATE all passed the test at the 1% significance level, which indicates that the results of matching between samples are relatively robust. The mean value of ATT is −0.0252, which suggests that cooperatives have a significant dampening effect on the poverty vulnerability of farm households. In other words, the poverty vulnerability of farmers who joined cooperatives was reduced by 0.0252 compared to those who did not join cooperatives.

## 4.3. Results of the heterogeneity analysis

### 4.3.1. Heterogeneity analysis based on educational level of household heads

The level of education of the household head is largely representative of the overall human capital endowment of the smallholder household. Therefore, we examine the heterogeneity of the effect of cooperatives on reducing the vulnerability of farm households to poverty in terms of the educational attainment of the

TABLE 1 Definition and descriptive statistics of the variables involved.

| Variables | Definition | Mean | SD |
|---|---|---|---|
| Dependent variables | | | |
| Vulnerability | Poverty vulnerability of smallholder households | 0.1414 | 0.2089 |
| Independent variables | | | |
| Cooperative | Whether or not to participate in a cooperative | 0.2429 | 0.4289 |
| Control variables | | | |
| Age | Age of the head of household (Years) | 48.8199 | 11.3194 |
| Gender | Gender of head of household. Female = 0; male = 1 | 0.6374 | 0.4808 |
| Education | Years of education of the head of household | 5.6535 | 4.3273 |
| Income | Logarithm of net household income *per capita* | 8.6364 | 1.2595 |
| Labor | Number of members in household aged 15–64 | 3.3083 | 1.6904 |
| Poverty | Whether the household is households registered as living under the poverty line. Yes = 1; No = 0 | 0.5720 | 0.3775 |
| Migrant | Whether there are family members working in the city. Yes = 1; No = 0 | 0.5758 | 0.4943 |
| Assets | Logarithm of total productive assets | 11.9661 | 1.1318 |
| S-capital | Logarithm of total gift expenses | 7.3053 | 2.0172 |
| Distance | Distance between the settlement and the county (km) | 51.9343 | 40.824 |
| Economic | Settled village economic status assessment | 4.1003 | 1.0108 |
| SiChuang | Whether the province is SiChuang. Yes = 1; No = 0 | 0.3218 | 0.1509 |
| YuNan | Whether the province is Yunnan. Yes = 1; No = 0 | 0.1849 | 0.2514 |
| ChongQing | Whether the province is ChongQing. Yes = 1; No = 0 | 0.3817 | 0.3499 |
| GuiZhou | Whether the province is Guizhou. Yes = 1; No = 0 | 0.1116 | 0.1724 |
| Observation | 1,622 | | |

TABLE 2 Baseline regression results of the impact of rural cooperatives on the poverty vulnerability of smallholder households.

| Variables | (1) | (2) | (3) |
|---|---|---|---|
| Cooperatives | −0.0443 *** (0.0112) | −0.0182 ** (0.0072) | −0.0162** (0.0076) |
| Age | 0.0032*** (0.0004) | 0.0036 *** (0.0002) | 0. 0036*** (0.0002) |
| Gender | 0.0424*** (0.0103) | 0.0282*** (0.0067) | 0.0246*** (0.0060) |
| Education | −0.0135 *** (0. 0011) | −0.0050 *** (0.0007) | −0.0039*** (0.0006) |
| Income | | −0.0897 *** (0. 0046) | −0.0763*** (0.0041) |
| Labor | | 0.0580*** (0.0018) | 0.0595 *** (0.0164) |
| Poverty | | 0.1332*** (0.0112) | 0.0452*** (0.0163) |
| S-capital | | −0.0039*** (0.0007) | −0.0035 *** (0.006) |
| Migrant | | 0.0198*** (0.0066) | 0.0175*** (0.0059) |
| Economic | | | −0.0072 (0.0199) |
| Distance | | | −0.0294*** (0.0014) |
| Province-FE | Yes | Yes | Yes |
| *N* | 1,622 | 1,622 | 1,622 |
| $R^2$ | 0.1464 | 0.6433 | 0.7165 |

The standard error is shown in parentheses. ** and *** are statistically significant at 5%,1% levels, respectively. Province-FE represents provincial fixed effects.

TABLE 3 Results of conditional independence hypothesis tests for explanatory variables before and after matching.

| Matching method | Ps $R^2$ | LR chi2 | MeanBias | B-value | Value of *p* |
|---|---|---|---|---|---|
| Unmatched | 0.013 | 24.27 | 7.8 | 37.9 | 0.002 |
| Nearest neighbor matching ($k = 4$) | 0.001 | 1.01 | 2.1 | 7.2 | 0.998 |
| Radius matching | 0.000 | 0.54 | 1.4 | 5.2 | 0.997 |
| Kernel matching | 0.000 | 0.51 | 1.4 | 5.1 | 0.999 |
| Mahalas matching | 0.001 | 1.30 | 1.5 | 8.1 | 0.996 |
| Partial linear regression matching | 0.002 | 3.81 | 1.6 | 7.6 | 0.874 |

household head. China has a 9-year compulsory education system. Based on China's school system, this paper classifies the years of education for heads of households into two categories, namely lower education group (0–9 years), and higher education group (more than 9 years).

As shown in Table 5, the effect of cooperatives on reducing poverty vulnerability is 2.05 times greater in the high quality group (−0.0387) than in the low quality group (−0.0188) for the education level of the household heads, which suggests that farmers with high quality human capital endowments are more likely to improve their poverty status after joining a cooperative than those with low quality. Hypothesis 3 was tested.

### 4.3.2. Heterogeneity analysis based on the level of household poverty

We divided the sample into two groups according to whether the households were registered as living under the poverty line or not. As shown in Table 6, cooperatives have a negative impact on the poverty vulnerability of farmers across different poverty attributes, but there are differences in the magnitude of the effect. The reduction effect of cooperatives on poverty vulnerability of non-poor households (0.0570) is 4.37 times greater than that of poor households (0.0130). This shows that non-poor households are more likely to benefit from co-operative seeds than poor households. Hypothesis 2 is verified.

### 4.3.3. Heterogeneity analysis based on the household incomes

This paper classifies farm households into lower-income and higher-income groups based on their median *per capita* income levels, and removes the variable of net household income from the regression. As shown in Table 7, the reduction effect of cooperatives on poverty vulnerability of higher income households is greater than that of lower income households. Overall, the cooperatives had a dampening effect on poverty vulnerability for both the lower and higher income groups of farmers, but there were differences in the magnitude of the effect, with a greater reduction effect for the higher income group than for the lower income group (−0.0406 > −0.0184), and hypothesis 4 is tested.

TABLE 4 Propensity score matching estimates of the impact of cooperatives on the poverty vulnerability of smallholder farmers.

| Matching method | ATT | ATU | ATE |
|---|---|---|---|
| Nearest neighbor matching ($k = 4$) | −0.0239** | −0.0299*** | −0.0265*** |
| Radius matching | −0.0235*** | −0.0284*** | −0.0272*** |
| Kernel matching | −0.0222*** | −0.0377*** | −0.0340*** |
| Mahalas matching | −0.0238** | −0.0335*** | −0.0288*** |
| Partial linear regression matching | −0.0324*** | −0.0229*** | −0.0276*** |
| Average value | −0.0252 | −0.0305 | −0.0288 |

The standard error is shown in parentheses. ** and *** are statistically significant at 5 and 1% levels, respectively. Significance tests for ATT, ATU, and ATE values were obtained using the bootstrap method of repeated sampling 500 times.

TABLE 5 Results of heterogeneity analysis on the relationship between the cooperatives and educational level of household heads.

| Variables | ATT | |
|---|---|---|
| | lower education (0–9 years) | higher education (more than 9 years) |
| Nearest neighbor matching ($k = 4$) | −0.0191* | −0.0463*** |
| Radius matching | −0.0179* | −0.0337** |
| Kernel matching | −0.0180* | −0.0440*** |
| Mahalas matching | −0.0121 | −0.0326*** |
| Partial linear regression matching | −0.0271** | −0.0369*** |
| Average value | −0.0188 | −0.0387 |

The standard error is shown in parentheses. *, ** and *** are statistically significant at 10, 5, and 1% levels, respectively. Significance tests for ATT, ATU, and ATE values were obtained using the bootstrap method of repeated sampling 500 times.

# 5. Discussion and conclusions

## 5.1. Discussions

Our explorations of the heterogeneous characteristics of smallholder farmers leads to a topic worth exploring, namely whether cooperatives in reality can meet the development aspirations of a wide range of disadvantaged groups and whether they really have the desired organizational effectiveness in driving smallholder farmers. According to classical co-operative theory, alleviating the inherent tension between smallholders and the larger market is the purpose of forming a cooperative for ‘weak’ smallholders (Lennard-Jones and Devonshire, 1939; Bleaney, 1963; Elliott et al., 1971). However, an important prerequisite for the effective operation of cooperatives is a high degree of homogeneity in membership. In reality, farmers are highly heterogeneous, and this is difficult to eliminate in the short term (Cai, 2002). As a result, the organizational objectives of cooperatives deviate from the assumptions of classical cooperative theory, and the organizational performance is biased toward members with superior resource endowments (Cai, 2002; Wagstaff et al., 2009). Thus, the organizational objectives of cooperatives deviated from the assumptions of classical cooperative theory, and organizational performance was biased in favor of members with superior resource endowments, so that the development and profitability of small farmers was reduced.

Cooperatives are an important vehicle for industrial poverty alleviation (Bernard and Spielman, 2009). The vast majority of studies have affirmed the positive role of cooperatives in reducing poverty and increasing income (Sun et al., 2009; Mojo et al., 2017). Cooperatives have an advantage over scattered smallholder farmers in terms of large-scale operation of farmland, use of advanced technology, coping with market risks and access to policy subsidies, increasing the added value, profitability, labor productivity and employment rate of farmers engaged in agricultural production (Sun et al., 2009; Babiarz et al., 2010). Co-operatives not only help farmers reduce transaction costs in the procurement of agricultural materials and agricultural production services, and increase their bargaining power in the marketing of agricultural products; they also provide a variety of training and activities to help farmers improve their viable capacity to access information, express their needs and apply technology, which helps reduce the poverty vulnerability of smallholder households (Dao et al., 2023).

In practice, some researchers have focused on the alienation of cooperatives caused by differences in groups of farmers (Dai et al., 2023; Zeren et al., 2023). Some co-operatives have evolved into ‘self-run enterprises’ that do not contribute to the development of their members, nor do they contribute to the incomes of farming households as a whole (Wilmsen et al., 2022; Dong et al., 2023). The natural heterogeneity of smallholder farmers in terms of their initial resource endowments, such as production and management capacity, risk tolerance and household livelihood capital, may lead to “elite capture,” resulting in deviated resources for poverty alleviation and misplaced project implementation, creating new income inequalities (Gilcrease et al., 2022). Some scholars also argue that small and medium-sized members of cooperatives are prone to “free-riding” behavior, unwilling to pay for the cooperative’s public services and enjoy the benefits without contributing much, affecting the efficiency of the organization’s operations and distributional equity (Ito et al., 2012).

TABLE 6 Results of heterogeneity analysis on the relationship between cooperatives and the poverty levels of farmers.

| Variables | ATT | |
|---|---|---|
| | Under the poverty line | Above the poverty line |
| Nearest neighbor matching ($k = 4$) | −0.0133** | −0.0407* |
| Radius matching | −0.0128** | −0.0548** |
| Kernel matching | −0.0068*** | −0.0623*** |
| Mahalas matching | −0.0132*** | −0.0655** |
| Partial linear regression matching | −0.0191** | −0.0617** |
| Average value | −0.0130 | −0.0570 |

The standard error is shown in parentheses. *, ** and *** are statistically significant at 10, 5 and 1% levels, respectively. Significance tests for ATT, ATU, and ATE values were obtained using the bootstrap method of repeated sampling 500 times.

TABLE 7 Results of heterogeneity analysis on the relationship between cooperatives and the household incomes.

| Variables | ATT | |
|---|---|---|
| | Lower income families | Higher income families |
| Nearest neighbor matching ($k = 4$) | −0.0173*** | −0.0458 *** |
| radius matching | −0.0181** | −0.0384** |
| kernel matching | −0.0168*** | −0.0423*** |
| Mahalas matching | −0.0202** | −0.0355** |
| partial linear regression matching | −0.0195** | −0.0413** |
| Average value | −0.0184 | −0.0406 |

The standard error is shown in parentheses. ** and *** are statistically significant at 5 and 1% levels, respectively. Significance tests for ATT, ATU, and ATE values were obtained using the bootstrap method of repeated sampling 500 times.

Heterogeneous characteristics make a difference in both the motivation of farmers to join and their factor inputs, resulting in differences in the impact of cooperatives on farmers' incomes (Gorczyca et al., 2022). It has been generally agreed that farmers with better resource endowments and more factor inputs are more likely to seek more control over their surplus. To accurately detect the impact of co-operatives on the poverty vulnerability of farm households, it is necessary to distinguish between the heterogeneity of farm households and focus on which groups co-operatives work more significantly for. The findings of this paper also confirm this phenomenon (Fernandes and Silva, 2022). Farmers whose heads have higher levels of education, non-poor families and higher household incomes have gained a more pronounced reduction in their poverty vulnerability after joining the cooperative. In research in less developed areas, poverty alleviation work generally suffers from strong policy input but weak endogenous motivation enhancement, etc. Most cooperatives only objectively absorb poor farmers into their societies as a matter of policy, but subjectively they do not pursue the effectiveness of bringing poverty, and are not willing to absorb poor farmers. In addition, the risk-averse nature of poor farmers with inherent lack of production endowments and social network resources often makes them reluctant to join the society, or even if they do, the shares they put in are low due to financial constraints, which inevitably leads to the problem that the cooperatives are "pro" the capable rural people and "anti" the disadvantaged (Bernard and Spielman, 2009; Chagwiza et al., 2016). The problem is that cooperatives are inevitably "pro" rural people and "pro" disadvantaged groups. However, it is also important to note that the value of cooperatives in benefiting the poor should not be dismissed because of their "affinity" to the rural and disadvantaged groups (Xu and Li, 2023). The empirical results also show that even if poor farmers find it difficult to participate in co-operatives because they are 'excluded' or less willing to join them, they can still benefit indirectly through the spillover effects of co-operatives.

Additionally, Farmers in different income brackets and education levels have different levels of involvement in the operations and management of the cooperative, leading to differences in their poverty vulnerability reduction. Farmers with less physical capital and less learning capacity have less control and say in the day-to-day operations of the cooperative, and tend to be in a lower position in the cooperative than those with more material resources and higher levels of education (Bouichou et al., 2021). Accordingly, cooperatives are also less effective in reducing their poverty vulnerability than members with superior physical capital and high levels of education. Conversely, farmers with strong economic resource endowments usually have sufficient accumulation of their own resource factors and can make full use of and effectively spill over their economic resource endowments (Alam et al., 2021). As a result, the decision to join the society is more effective and more rewarding for these farmers.

### 5.2. Conclusion

Based on micro-survey data from smallholder farmers in eight counties in four provinces in the underdeveloped regions of western China, this paper analyses the impact of farmers' membership in cooperatives on their poverty vulnerability and further explores the differences in the poverty reduction effects of cooperatives on groups with different poverty attributes, different human capital endowments (education level of the household head), and different income class heterogeneity. The main conclusions are as follows.

1. (1) Cooperatives have a significant dampening effect on the poverty vulnerability of smallholder farmers. Cooperatives have a positive external impact in terms of helping farmers to overcome barriers to market access, accelerating the formation of human (social) capital and empowering management, which in turn has a combined effect on improving the ability of farmers to develop themselves, which has a combined effect on the improvement and enhancement of farmers' capacity for autonomous development.
2. (2) After overcoming the sample selection bias using the PSM model, the results show that participation in cooperatives still reduces the poverty vulnerability of smallholder farmers by an average of −0.0252, and the result remains robust to multiple tests of the methodology.
3. (3) The impact of cooperatives on the poverty vulnerability of smallholder farmers is significantly heterogeneous across groups. Specifically, participation in cooperatives has a more pronounced effect on poverty reduction among non-poor, higher human capital endowment and higher income bracket households than among poor, lower human capital endowment and lower income bracket households.

The validated conclusions outlined above can contribute and assist in emerging policy enlightenment. Firstly, enhancing the linkages between the interests of rural 'elite' figures and 'weak' small farmers. Policy makers should guide and encourage farmers to join or start cooperatives and support the development of cooperatives as an effective initiative to reduce poverty among smallholder farmers, but they should also see the limitations of the effectiveness of policy implementation. A top-down push for cooperative development and the pursuit of incremental growth in order to achieve an increase in the ability of farmers to reduce poverty will likely lead to a further widening of the gap in the ability of farmers to escape poverty in the future. The government should, on the basis of cultivating the stock of cooperatives, keenly identify the fit between "elite" figures and "weak" small farmers in terms of business areas and cooperative relationships, and strengthen the linkage between the interests of cooperatives and small farmers in order to minimize the negative effect of "elite capture." Secondly, cooperatives are an effective way for smallholder farmers in less developed areas to escape poverty. Even if poor farmers find it difficult to participate in cooperatives because they are 'excluded' or have a low willingness to join, they can still benefit indirectly through the spillover effects of cooperatives.

There are still many limitations in this paper, which can be seen in the following aspects: Firstly, we have focused more on the heterogeneity of farmers and neglected the heterogeneity of the cooperatives themselves. The variables in this paper are selected from the perspective of farmers only, and are based on a single dimensional characteristic of farmers, without detailed descriptions and statistics of cooperatives. Second, the paper does not consider the willingness of cooperatives to take on board. Whether farmers can become members of cooperatives is not only based on whether they have a demand for membership, but also on whether cooperatives have the willingness to open up membership to the public, which is the result of a combination of demand and supply factors. However, on the supply side, the willingness of cooperatives to take up membership varies depending on the organizational model, governance and other characteristic factors of cooperatives in less developed western regions. Thirdly, social capital and the governance model of cooperatives play an important role in the poverty reduction effect of rural cooperatives. However, we did not conduct an in-depth analysis of these two areas due to the availability of data. Finally, the paper does not include the factors of policy intervention in cooperatives in its examination. If the policy is to support excellence and strength, cooperatives will choose to exclude the rural disadvantaged because they want to improve their competitiveness; in contrast, if the policy is to regulate the development of cooperatives and advocate their pro-poor attributes, then the relevant policy interventions will affect the exclusion decision of cooperatives as well as the demand of farmers to join the society. Policy interventions affect both the willingness of co-operatives to take in and the demand of farmers to join. The construction of an analytical framework that incorporates policy interventions, cooperative and farmer characteristics is an important direction for future research.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

MY: conceptualization, validation, data curation, and supervision. ZZ: methodology and resources. MY and JL: software, writing—original draft preparation, writing—review and editing, and visualization. JL, MY, and JL: formal analysis. JL: investigation. All authors have read and agreed to the published version of the manuscript.

## Funding

This research was financially supported by the National Social Science Fund of China (Grant/Award Number: 17XTQ011); the MOE Project of Key Research Institute of Humanities and Social Sciences in Universities of China (Grant/Award Number: 16JJD790063); the National Social Science Foundation Youth Project of China (Grant/Award Number: 16JJD79006321CJY044).

## Acknowledgments

The authors acknowledge funding from the National Social Science Foundation of China and the MOE Project of Key Research Institute of Humanities and Social Sciences in Universities of China.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## References

Ajates, R. (2020). An integrated conceptual framework for the study of agricultural cooperatives: from repolitisation to cooperative sustainability. *J. Rural. Stud.* 78, 467–479. doi: 10.1016/j.jrurstud.2020.06.019

Ajates, R. (2021). Reducing the risk of co-Optation in alternative food networks: multi-stakeholder cooperatives, social capital, and third spaces of cooperation. *Sustainability* 13:1219. doi: 10.3390/su132011219

Alam, Z., Watanabe, Y., Hanif, S., Sato, T., and Fujimoto, T. (2021). Community-based business on small hydropower (SHP) in rural Japan: a case study on a community owned SHP model of Ohio agricultural cooperative. *Energies* 14:3349. doi: 10.3390/en14113349

An, J., Cho, S. H., and Tang, C. S. (2015). Aggregating smallholder farmers in emerging economies. *Prod. Oper. Manag.* 24, 1414–1429. doi: 10.1111/poms.12372

Babiarz, K. S., Miller, G., Yi, H., Zhang, L., and Rozelle, S. (2010). New evidence on the impact of China's new rural cooperative medical scheme and its implications for rural primary healthcare: multivariate difference-in-difference analysis. *BMJ Br. Med. J.* 341:c5617. doi: 10.1136/bmj.c5617

Bacon, C. M., Sundstrom, W. A., Flores Gómez, M. E., Ernesto Méndez, V., Santos, R., Goldoftas, B., et al. (2014). Explaining the 'hungry farmer paradox': smallholders and fair trade cooperatives navigate seasonality and change in Nicaragua's corn and coffee markets. *Glob. Environ. Change Human Policy Dimens.* 25, 133–149. doi: 10.1016/j.gloenvcha.2014.02.005

Bender, M. (1999). Economic feasibility review for community-scale farmer cooperatives for biodiesel. *Bioresour. Technol.* 70, 81–87. doi: 10.1016/s0960-8524(99)00009-7

Bernard, T., and Spielman, D. J. (2009). Reaching the rural poor through rural producer organizations? A study of agricultural marketing cooperatives in Ethiopia. *Food Policy* 34, 60–69. doi: 10.1016/j.foodpol.2008.08.001

Bernard, T., and Taffesse, A. S. (2012). Returns to scope? Smallholders commercialisation through multipurpose cooperatives in Ethiopia. *J. Afr. Econ.* 21, 440–464. doi: 10.1093/jae/ejs002

Bernard, T., Taffesse, A. S., and Gabre-Madhin, E. (2008). Impact of cooperatives on smallholders' commercialization behavior: evidence from Ethiopia. *Agric. Econ.* 39, 147–161. doi: 10.1111/j.1574-0862.2008.00324.x

Beuchelt, T. D., and Zeller, M. (2013). The role of cooperative business models for the success of smallholder coffee certification in Nicaragua: a comparison of conventional, organic and organic-Fairtrade certified cooperatives. *Renew. Agric. Food Syst.* 28, 195–211. doi: 10.1017/s1742170512000087

Bleaney, B. (1963). Crystal field effects and co-operative STATE.1. A primitive theory. *Proc. Royal Soc. London Series A Math. Phys. Sci.* 276:19. doi: 10.1098/rspa.1963.0189

Bouichou, E., Abdoulaye, T., Allali, K., Bouayad, A., and Fadlaoui, A. (2021). Entrepreneurial intention among rural youth in Moroccan agricultural cooperatives: the future of rural Entrepreneurship. *Sustainability* 13:9247. doi: 10.3390/su13169247

Cafer, A. M., and Rikoon, J. S. (2018). Adoption of new technologies by smallholder farmers: the contributions of extension, research institutes, cooperatives, and access to cash for improving tef production in Ethiopia. *Agric. Hum. Values* 35, 685–699. doi: 10.1007/s10460-018-9865-5

Cai, L. P. A. (2002). Cooperative branding for rural destinations. *Ann. Tour. Res.* 29, 720–742. doi: 10.1016/s0160-7383(01)00080-9

Chagwiza, C., Muradian, R., and Ruben, R. (2016). Cooperative membership and dairy performance among smallholders in Ethiopia. *Food Policy* 59, 165–173. doi: 10.1016/j.foodpol.2016.01.008

Cheng, J. J., Wang, Q., Li, D., and Yu, J. (2022). Comparative analysis of environmental and economic performance of agricultural cooperatives and smallholder farmers for apple production in China. *Agric. Basel* 12:1281. doi: 10.3390/agriculture12081281

Dai, Q. Y., Ding, L., Zhang, Z., Zhu, Y., and Shi, Y. (2023). Determining the optimal operation and maintenance contract period of PV poverty alleviation projects based on real options and cooperative game: evidence from rural China. *J. Renew. Sustain. Energy* 15:023702. doi: 10.1063/5.0134751

Dao, Z., Sanogo, K., and Ahognisso, A. A. (2023). Cooperative entrepreneurship and autonomization of rural women in Cote d'ivoire. *J. Dev. Entrep.* 28:36. doi: 10.1142/s1084946723500036

Deng, L., Chen, L., Zhao, J., and Wang, R. (2021). Comparative analysis on environmental and economic performance of agricultural cooperatives and smallholder farmers: the case of grape production in Hebei, China. *PLoS One* 16:e0245981. doi: 10.1371/journal.pone.0245981

Deng, H. S., Huang, J., Xu, Z., and Rozelle, S. (2010). Policy support and emerging farmer professional cooperatives in rural China. *China Econ. Rev.* 21, 495–507. doi: 10.1016/j.chieco.2010.04.009

Dong, T. F., Zha, Z. Q., Sun, L., Liu, L. L., Li, X. Y., Wang, Y., et al. (2023). Ambient nitrogen dioxide and cardiovascular diseases in rural regions: a time-series analyses using data from the new rural cooperative medical scheme in Fuyang, East China. *Environ. Sci. Pollut. Res.* 30, 51412–51421. doi: 10.1007/s11356-023-25922-9

Elliott, R. J., Gehring, G. A., Malozemoff, A. P., Smith, S. R. P., Staude, W. S., and Tyte, R. N. (1971). Theory of co-operative Jahn-teller distortions in dyvo4 and TBVO4. *J. Phys. C Solid State Phys.* 4:L179. doi: 10.1088/0022-3719/4/9/013

Fan, Q., and Garcia, V. B. S. (2018). Information access and smallholder Farmers' market participation in Peru. *J. Agric. Econ.* 69, 476–494. doi: 10.1111/1477-9552.12243

Fernandes, J. A. F., and Silva, L. D. A. (2022). Business strategy of four small chilean agricultural cooperatives for rural development. *Desenvolvimento E Meio Ambiente* 60, 567–589. doi: 10.5380/dma.v60i0.75895

Gilcrease, W., DiCosmo, V., and Padovan, D. (2022). Trends of rural electric cooperatives in the United States from 1990 to 2019: An empirical analysis. *Renew. Sustain. Energy Rev.* 166:112641. doi: 10.1016/j.rser.2022.112641

Gorczyca, A. M., Washburn, R. A., Smith, P., Montgomery, R. N., Koon, L. M., Hastert, M., et al. (2022). Feasibility and comparative effectiveness for the delivery of the National Diabetes Prevention Program through cooperative extension in rural communities. *Int. J. Environ. Res. Public Health* 19:9902. doi: 10.3390/ijerph19169902

Grashuis, J., and Su, Y. (2019). A review of the empirical LITERATURE on farmer cooperatives: performance, ownership and governance, finance, and member attitude. *Ann. Public Cooperat. Econ.* 90, 77–102. doi: 10.1111/apce.12205

Ishak, S., Omar, A. R. C., Sum, S. M., Othman, A. S., and Jaafar, J. (2020). Smallholder agriculture cooperatives' performance: what is in the minds of management? *J. Co-Operat. Organ. Manag.* 8:100110. doi: 10.1016/j.jcom.2020.100110

Ito, J., Bao, Z. S., and Su, Q. (2012). Distributional effects of agricultural cooperatives in China: exclusion of smallholders and potential gains on participation. *Food Policy* 37, 700–709. doi: 10.1016/j.foodpol.2012.07.009

Jia, S., and Xu, X. B. (2021). Community-level social capital and agricultural cooperatives: evidence from Hebei, China. *Agribusiness* 37, 804–817. doi: 10.1002/agr.21703

Jitmun, T., Kuwornu, J. K. M., Datta, A., and Kumar Anal, A. (2020). Factors influencing membership of dairy cooperatives: evidence from dairy farmers in Thailand. *J. Co-Operat. Organ. Manag.* 8:100109. doi: 10.1016/j.jcom.2020.100109

Kumar, A., Saroj, S., Joshi, P. K., and Takeshima, H. (2018). Does cooperative membership improve household welfare? Evidence from a panel data analysis of smallholder dairy farmers in Bihar, India. *Food Policy* 75, 24–36. doi: 10.1016/j.foodpol.2018.01.005

Lennard-Jones, J. E., and Devonshire, A. F. (1939). Critical and co-operative phenomena III. A theory of melting and the structure of liquids. *Proc. Royal Soc. London Series a-Math. Phys. Sci.* 169, 317–0338. doi: 10.1098/rspa.1939.0002

Li, M., Yan, X., Guo, Y., and Ji, H. (2021). Impact of risk awareness and agriculture cooperatives' service on farmers' safe production behaviour: evidences from Shaanxi Province. *J. Clean. Prod.* 312:127724. doi: 10.1016/j.jclepro.2021.127724

Liang, Q., Zuhui, H., Haiyang, L., and Xinxin, W. (2015). Social capital, member participation, and cooperative performance: evidence from China's Zhejiang. *Int. Food Agribus. Manag. Rev.* 18, 49–78.

Loconto, A. M., and Simbua, E. F. (2012). Making room for smallholder cooperatives in Tanzanian tea production: can Fairtrade do that? *J. Bus. Ethics* 108, 451–465. doi: 10.1007/s10551-011-1101-9

Ma, W. L., and Abdulai, A. (2016). Does cooperative membership improve household welfare? Evidence from apple farmers in China. *Food Policy* 58, 94–102. doi: 10.1016/j.foodpol.2015.12.002

Ma, W. L., and Abdulai, A. (2017). The economic impacts of agricultural cooperatives on smallholder farmers in rural China. *Agribusiness* 33, 537–551. doi: 10.1002/agr.21522

Ma, B. J., and Jin, X. (2022). Does internet use connect us to a healthy diet? Evidence from rural China. *Nutrients* 14:2630. doi: 10.3390/nu14132630

Mavimbela, P., Masuku, M. B., and Belete, A. (2010). Contribution of savings and credit cooperatives to food crop production in Swaziland: a case study of smallholder farmers. *Afr. J. Agric. Res.* 5, 2868–2874.

Meador, J. E., O'Brien, D., Cook, M., Grothe, G., Werner, L. A., Diang'a, D., et al. (2016). Building sustainable smallholder cooperatives in emerging market economies: findings from a five-year project in Kenya. *Sustainability* 8:656. doi: 10.3390/su8070656

Mojo, D., Fischer, C., and Degefa, T. (2017). The determinants and economic impacts of membership in coffee farmer cooperatives: recent evidence from rural Ethiopia. *J. Rural. Stud.* 50, 84–94. doi: 10.1016/j.jrurstud.2016.12.010

Person, M. T., Delea, M. G., Garn, J. V., Alexander, K., Abaire, B., and Freeman, M. C. (2017). Assessing the influence of social capital on water point sustainability in rural Ethiopia. *J. Water Sanit. Hyg. Dev.* 7, 611–622. doi: 10.2166/washdev.2017.167

Richards, M. B., and Mendez, V. E. (2014). Interactions between carbon sequestration and shade tree diversity in a smallholder coffee cooperative in El Salvador. *Conserv. Biol.* 28, 489–497. doi: 10.1111/cobi.12181

Saz-Gil, I., Bretos, I., and Diaz-Foncea, M. (2021). Cooperatives and social capital: a narrative Literature review and directions for future research. *Sustainability* 13:534. doi: 10.3390/su13020534

Scripcariu, I. S., Grigore, M., Balcan, L., and Petroaie, A. D. (2020). A call to action: gaps in dietary awareness among pregnant Women in north eastern Romania. *Revista De Cercetare Si Interventie Sociala* 69, 437–447. doi: 10.33788/rcis.69.28

Shi, J., Zhao, Y., Kiwanuka, R. B. K., and Chang, J. (. A.). (2019). Optimal selling policies for farmer cooperatives. *Prod. Oper. Manag.* 28, 3060–3080. doi: 10.1111/poms.13091

Sun, X. Y., Jackson, S., Carmichael, G., and Sleigh, A. C. (2009). Catastrophic medical payment and financial protection in rural China: evidence from the new cooperative medical scheme in Shandong province. *Health Econ.* 18, 103–119. doi: 10.1002/hec.1346

Tadesse, G., Abate, G. T., and Ergano, K. (2019). The boundary of smallholder Producers' cooperatives: a conceptual and empirical analysis. *J. Agric. Econ.* 70, 529–549. doi: 10.1111/1477-9552.12310

Tray, B., Garnevska, E., and Shadbolt, N. (2021). Linking smallholder producers to high-value markets through vegetable producer cooperatives in Cambodia. *Int. Food Agribus. Manag. Rev.* 24, 905–920. doi: 10.22434/ifamr2020.0135

Valkila, J., and Nygren, A. (2010). Impacts of fair trade certification on coffee farmers, cooperatives, and laborers in Nicaragua. *Agric. Hum. Values* 27, 321–333. doi: 10.1007/s10460-009-9208-7

van Rijsbergen, B., Elbers, W., Ruben, R., and Njuguna, S. N. (2016). The ambivalent impact of coffee certification on Farmers' welfare: a matched panel approach for cooperatives in Central Kenya. *World Dev.* 77, 277–292. doi: 10.1016/j.worlddev.2015.08.021

Verhofstadt, E., and Maertens, M. (2014). Smallholder cooperatives and agricultural performance in Rwanda: do organizational differences matter? *Agric. Econ.* 45, 39–52. doi: 10.1111/agec.12128

Verhofstadt, E., and Maertens, M. (2015). Can agricultural cooperatives reduce poverty? Heterogeneous impact of cooperative membership on Farmers' welfare in Rwanda. *Appl. Econ. Perspect. Policy* 37, 86–106. doi: 10.1093/aepp/ppu021

Wagstaff, A., Lindelow, M., Jun, G., Ling, X., and Juncheng, Q. (2009). Extending health insurance to the rural population: An impact evaluation of China's new cooperative medical scheme. *J. Health Econ.* 28, 1–19. doi: 10.1016/j.jhealeco.2008.10.007

Wang, Z., Yang, M., Zhang, Z., Li, Y., and Wen, C. (2022). The impact of land transfer on vulnerability as expected poverty in the perspective of farm household heterogeneity: An empirical study based on 4608 farm households in China. *Land* 11:1995. doi: 10.3390/land11111995

Wilmsen, B., Rogers, S., Duan, Y., and Wang, J. H. Z. (2022). Farmer cooperatives and the limits of agricultural reform in rural Hubei. *China J.* 89, 1–23. doi: 10.1086/722258

Wollni, M., and Zeller, M. (2007). Do farmers benefit from participating in specialty markets and cooperatives? The case of coffee marketing in Costa Rica. *Agric. Econ.* 37, 243–248. doi: 10.1111/j.1574-0862.2007.00270.x

Xu, N., and Li, C. A. (2023). Migration and rural sustainability: relative poverty alleviation by geographical mobility in China. *Sustainability* 15:6248. doi: 10.3390/su15076248

Yang, M., Zhang, Z., and Wang, Z. (2023). Does internet use connect smallholder farmers to a healthy diet? Evidence from rural China. *Front. Nutr.* 10:1122677. doi: 10.3389/fnut.2023.1122677

Yin, Z. N., Errisuriz, V. L., Evans, M., Inupakutika, D., Kaghyan, S., Li, S., et al. (2020). A digital health intervention for weight Management for Latino Families Living in rural communities: perspectives and lessons learned during development. *Jmir Format. Res.* 4:e20679. doi: 10.2196/20679

Zeren, G. B., Tan, J., Zhang, Q., and Qiuying, B. (2023). Rebuilding rural community cooperative institutions and their role in herder adaptation to climate change. *Clim. Pol.* 23, 522–537. doi: 10.1080/14693062.2023.2184763

Zhang, W. F., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., et al. (2016). Closing yield gaps in China by empowering smallholder farmers. *Nature* 537, 671–674. doi: 10.1038/nature19368

Zhang, Y. J., Liu, J. Y., and Woodward, R. T. (2023). Has Chinese certified emission reduction trading reduced rural poverty in China? *Aust. J. Agric. Resour. Econ.* 67, 438–458. doi: 10.1111/1467-8489.12515

# Frontiers in
# Sustainable Food Systems

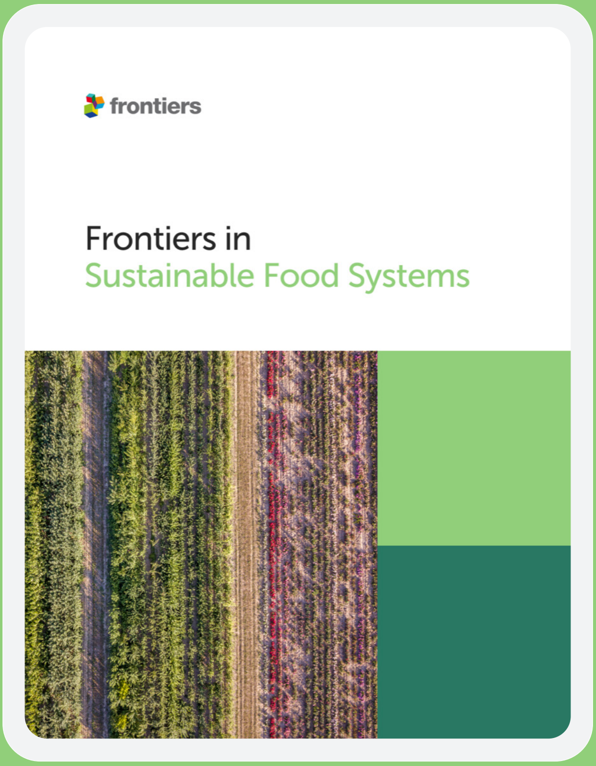
**Exploring sustainable solutions to global food security**

Aligned with the UN Sustainable Development Goals, this journal explores the intersection of food systems, science and practice of sustainability including its environmental, economic and social justice dimensions.

---

## Discover the latest Research Topics

See more →



frontiers

Frontiers in
Sustainable Food Systems

**Frontiers**

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

**Contact us**

+41 (0)21 510 17 00
frontiersin.org/about/contact