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Enhancing food production system resilience for food security facing a changing environment

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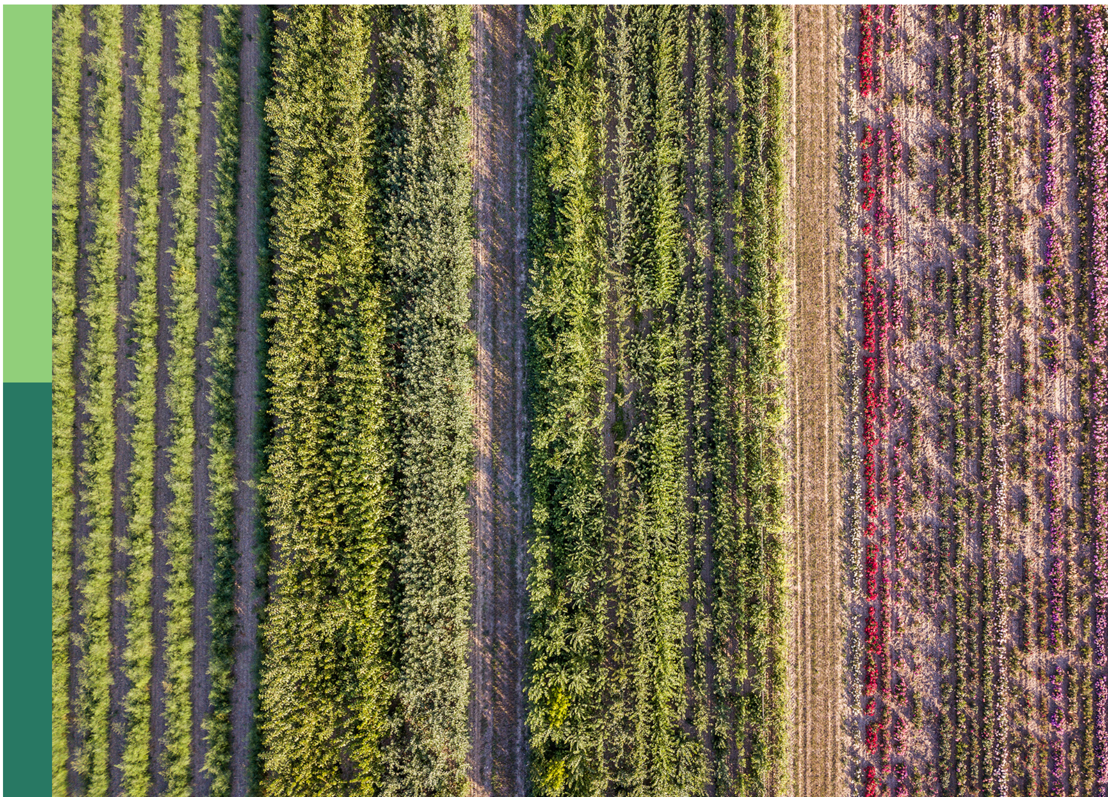

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Enhancing food production system resilience for food security facing a changing environment

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Editorial: Enhancing food production system resilience for food security facing a changing environment

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Editorial on the Research Topic
Enhancing food production system resilience for food security facing a changing environment

As the dominant source of the human food supply, the global land system underlies the foundation of the livelihood and wellbeing of humanity on Earth (FAO, 2022). On the one hand, the growth rate of the land system's production capacity for food has played a key role in global food provision. Technological breakthroughs in wheat and rice production during the past few decades, for instance, have greatly contributed to the maintenance of this growth rate in many parts of the world (Ye and Van Ranst, 2009). On the other hand, the terrestrial food production system is facing increasing challenges from environmental stressors ranging from climate change and air pollution to land degradation. Whether and how the global land system will support the food security of more than 10 billion people in the twenty first century while minimizing its environmental footprint remains open to debate (Meyfroidt et al., 2022). It is inevitable that the global food production system must shift its focus from expansion of production to land system resilience so that the dual goals of sustainable production and environmental friendliness can be simultaneously achieved.

In line with these perspectives, this Research Topic has published 12 articles, consisting of 11 research articles and one review article. The research articles are predominantly by authors from the Global South, showing a close association between the scientific community and the general public in these countries. The articles published as part of this Research Topic highlight ongoing hotspots in the current food system-related research landscape (Figure 1). These include income boosting (Zondi et al.), household food security and welfare (Olawuyi et al.), protection of crops and livestock from ongoing disease outbreaks and epidemics (Li et al.; Nanyiti et al.), yield trends (Wang et al.), policy interventions relating to the food (Neupane, Paudel et al.) and energy sectors (Neupane, Chaudhary et al.) under climate change, and the application of digital, geospatial, and remote sensing technologies to inform precision management (Chen et al.) and adaptation (Fu and Zhang; Varela et al.). Moreover, this Research Topic has also published forward-thinking articles focusing on integrated solutions (Yusriadi and Cahaya) and alternative foods (Siedenburg) that can help to build a more resilient food system for decades to come.

FIGURE 1
Components of food production system resilience, evaluated based on the articles published in this Research Topic.

It has been found that maintaining a stable supply has primary significance in ensuring food security at the regional to national scales. Based on a provincial panel dataset on rice production in six southern provinces in China between 2007 and 2017, Wang et al. investigated 710 high-quality rice varieties and found that yields of both *indica* and *japonica* rice increased significantly, illustrating the growing importance of rice crops in providing global food solutions. This is important because the reported yield increase was obtained for high-quality varieties, for which a stable increase in regional yield is more difficult to realize in comparison to hybrid varieties (Yuan, 2017). Similar to rice in Asia, cassava is an important staple crop in Africa and is a major source of carbohydrates for some 800 million people worldwide. Nanyiti et al. collected field data from Uganda and found that aphids can infect cassava plants with cassava brown streak disease (CBSD), causing devastating yield losses. This is the first report of CBSD infection by aphids in Uganda, revealing a new vector of transmission for cassava brown streak viruses. Furthermore, Li et al. stress the importance of biosecurity measures in livestock production systems. As the authors indicate, African swine fever (ASF) is the greatest challenge to the sustainable development of pig farming in many regions. By analyzing data from 351 pig farmers in Sichuan province in China, Li et al. statistically tested the effectiveness of government regulations against ASF. Based on their largely positive results, the authors recommend that government-mandated biosecurity measures should be continued and strengthened to curb future outbreaks.

It has also been found that new technologies and forward thinking are important pathways to improved resilience in future food production systems. Using GIS-based climate vulnerability maps, Varela et al. showed that well-timed adjustments to local cropping systems could avoid large losses caused by adverse climatic conditions; they therefore urge the development of harmonized measures in building agricultural adaptive capacity against climate change. Similarly, Chen et al. adopted a coupled remote sensing imagery approach to automatic garlic mapping in the North China Plain, demonstrating the role of satellite and other digital technologies (Fu and Zhang) in the precision management of essential crops in the food system. Yusriadi and Cahaya go one step further in provocative food system thinking, highlighting the need for interventions that include components relating to environmental conservation and social structures for a food-secure future. As the author of the sole review article presented in this Research Topic, Siedenburg argues persuasively that microalgae, a diverse group of microscopic aquatic organisms, could be used as a food, feed, biofertilizer, biostimulant, and biochar material, despite continuing issues with consumer acceptance, affordability, and food safety concerns.

Attention is merited not only to the technological aspects of building resilience into the current food production system, but also to the social and policy aspects of the challenge. Zondi et al. call for a clear government support plan for the vulnerable group of indigenous crop farmers in South Africa, while Olawuyi et al. report, based on their survey data collected from Nigeria, that women are disproportionately food-insecure under economic shocks and environmental stressors. These authors recommend careful planning of public investments, considering the special needs of vulnerable groups to build the capacity for resilience and to support wellbeing at the household level. In a broader context, following "systems" thinking offers a better approach to building resilience in food production systems (Neupane, Paudel et al.; Neupane, Chaudhary et al.), where a nexus approach to integrated planning, policy coherence, and institutional harmonization will enhance not only food security but also water and energy security, and lead to a higher quality of life.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

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

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Factors Influencing the Extent of the Commercialization of Indigenous Crops Among Smallholder Farmers in the Limpopo and Mpumalanga Provinces of South Africa

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Smallholder farmers encounter countless challenges that not only restrict them from maximizing market opportunities but also limit their access to the markets. This paper aims to achieve a thorough understanding of the factors that influence the market participation of indigenous crops by smallholder farmers while also analyzing the extent of market participation in South Africa. An analyzable sample size of 1,520 was used for the study. Household commercialization index (HCI), *T*-test, description analysis, and a double hurdle model with quasi-maximum likelihood fractional response model were employed to analyze the commercialization and extent of commercialization among indigenous crops by smallholder farmers in South Africa. The study demonstrated that a farmer's decision to participate in the market is highly dependent on gender, off-farm income, access to market information, and a family member being infected by HIV. Factors such as household size and access to the market had statistical significance in the extent of market participation by smallholder farmers. While we recommend the need to intensify appropriate training for farmers and extension workers involved in the area of indigenous crops, it is also important that indigenous crops are given the necessary considerations by the government and research institutions so that their demand in the market could increase. There is a need to develop a clear support plan for the few farmers that have decided to be involved in the farming of indigenous crops even though they are not highly marketable. On the other hand, there is also a need for consumer awareness campaigns in South Africa, on the income and nutritional benefits of indigenous crops.

Keywords: smallholder farmers, indigenous crops, household commercialization index, double-hurdle fractional response model, South Africa

INTRODUCTION

The agricultural sector is the backbone of many South African households (Pawlak and Kołodziejczak, 2020). The majority of households residing in rural areas not only depend on agriculture for their livelihoods and well-being but also are involved in subsistence agriculture which is characterized by a combination of crop and animal production (Shackleton et al., 2001; Gautam and Andersen, 2016). As reported by Statistics South Africa (2019) in the General Household Survey report, about 15.3% of the households in South Africa are involved in agriculture. Some of the crops being produced by these households are ecologically resilient indigenous crops that can withstand a changing climate and other challenges (Akinola et al., 2020). "Indigenous crops are defined as plant species that are either genuinely native to a particular region, or which were introduced to that region for long enough to have evolved through natural processes or farmer selection" (Mahlangu, 2014). These crops are not only a source of income for several smallholder farmers but also the primary source of nutrients for food and nutritional security. Furthermore, they can contribute to sustainable food systems under climate change since they are ecologically resilient (Akinola et al., 2020; Hlatshwayo et al., 2021). Gitz et al. (2017) reported that about 70% of the poor residing in rural areas, completely or partially depend on indigenous crops for their livelihoods. However, smallholder farmers especially in developing countries are faced with numerous constraints that hinder their commercialization of indigenous crops (Meemken and Bellemare, 2020).

Smallholder farmers are faced with a lack of production and marketing knowledge, information, and skills that could enable them to compete with commercial farmers (Minot and Sawyer, 2016). Moreover, the majority of smallholder farmers are also faced with poor quality infrastructure, inadequate storage facilities and transport, and are associated with a lack of information and skills which leads to high transaction costs of participating in the market and hence, over-reliance on traditional social networks and mechanisms for marketing their produce (Ali et al., 2021). Some smallholder farmers still use bartering or gifts to exchange or obtain seeds and crops.

The literature also revealed that other factors that affect the commercialization of indigenous crops are socio-demographic factors such as education level, market information access, HIV status, source of income, and age (Key et al., 2000; Adenegan and Adewusi, 2007; Lubungu et al., 2012; Dlamini-Mazibuko et al., 2019). Smallholder farmers in South Africa are generally illiterate, aged and lack market information (Hlatshwayo et al., 2021). Smallholder farmers operate on small pieces of land which leaves them with no choice but to consume most of their produce with a minimum to sell (Rapsomanikis, 2015). Lack of land possession limits farmers from engaging in long-term investment and makes it difficult for them to access credit. Also, the government and policymakers do not recognize them and hence the benefits of indigenous crops remain unknown (Von Loeper et al., 2016).

While some studies (Karaan et al., 2006; Akinnifesi et al., 2007; Akinola et al., 2020) have been conducted in Africa on several agricultural experiments with regards to indigenous crops and their economic potential, South Africa does not have much information on the factors that affect the participation of smallholder farmers in the commercialization of indigenous crops. Mahlangu (2014) reported that there is a market for indigenous crops and, therefore, it is important to understand the impact of market participation on the livelihoods of smallholder farmers in South Africa. Lack of knowledge on the impact of marketing the indigenous crops could be the reason why some smallholder farmers are not participating in the market in the first place. The provision of information on the benefits of commercializing these crops together with the strategies to address the factors that affect their market participation will be useful to smallholder farmers and may not only influence them but also open up opportunities for them to grow for commercial purposes. Understanding the contribution of indigenous crops toward rural households or smallholder farmers' livelihoods and food security can raise awareness with regard to effective participation. They can adopt strategies to grow these and sell them to the market. The information will be useful in the implementation and formulation of relevant strategies to commercialize indigenous crops effectively.

The main purpose of this study was to identify the factors that influence the commercialization and the extent of the commercialization of indigenous crops among smallholder farmers since very little is known about the issue. It was clear from the literature that some farmers had been suffering from a lack of market information, farming equipment, and support from extension services. This should be addressed as it results in farmers making poor decisions about which channels of the market to participate in. Lastly, in line with its objective, this study has provided recommendations that will help the government with information about the importance of allowing smallholders to participate in the market, and policymakers to recognize the role of smallholder farmers in market participation.

RESEARCH METHODOLOGY

The Study Area Description

This study was conducted in the Northern and North-East Regions of South Africa covering about two of the nine provinces in South Africa. Limpopo and Mpumalanga provinces are populated by smallholder communal farmers that mainly depend on agricultural and livestock farming for their livelihoods. Limpopo is situated in the Northern part of South Africa, covering about 125,754 km² of the area, which is only 10.2% of the total area of the country. Its population is about 5,8 million with five districts of Mopani, Vhembe, Capricorn, Waterberg and Sekhukhune (Christopher, 2017). The people in this province are highly involved and dependent on agriculture for survival, as 89% of the peoples' occupation is agriculture. The study was conducted in the districts mentioned above.

The second study area is Mpumalanga province, which is located in the North-Eastern part of South Africa. It covers about 6.5% of the country's land area. It consists of about 4.04 million people with 72% being involved in agriculture (Christopher, 2017). The overall rainfall received in this province per year is about 1,000 mm, with its warm and temperate weather conditions

TABLE 1 | Indigenous crops grown by Limpopo and Mpumalanga Smallholder farmers.

Indigenous crops	Scientific names
Amadumbe	*Colocasia esculenta*
Bambara groundnut	*Vigna subterranea*
Cassava	*Manihot esculenta*
Cowpea	*Vigna unguiculata*
Eggplant	*Solanum melongena*
Leafy vegetables	
Millet	*Panicum miliaceum*
Okra	*Abelmoschus esculentus*
Pumpkin	*Cucurbita*
Sorghum	*Sorghum bicolor*

Source: Mabhaudhi et al. (2017).

as it lies 665m above sea level. This province contributes to the agricultural economy through farms produce such as corn (maize), sugar, cotton, groundnuts, potatoes, wheat, and indigenous crops such as Amaranth, Vegetable Cow-pea, African eggplant, Okra and pumpkin (Lehohla, 2016). A variety of fruit is also produced in this province including mangoes and oranges in the subtropical low-veld, whereas peaches are produced at higher elevations.

Data Types, Sources and Methods of Data Collection

While the data analyzed in this study focuses on two provinces, the research was part of a bigger baseline assessment study that was conducted in four provinces in South Africa. Therefore, the data used in this study has been extracted from an assessment study that was conducted in various provinces of South Africa by the South African Vulnerability Assessment Committee (SAVAC), led by the Secretariat hosted in the Department of Agriculture, Land Reform and Rural Development (DALRRD) in 2016. Data collected included the demographics of the participants, crops (indigenous and cash crops) produced and consumed by rural households, food security and nutrition information. However, the purpose of this particular study is to assess the factors influencing the extent of indigenous crops' smallholder farmers' market participation. Smallholder farmers were asked to list the different types of crops they produce, consume and sell. From the list of crops identified by the smallholder farmers, indigenous crops were selected (**Table 1**).

The study used a quantitative research method to collect data. The multi-stage stratified random sampling technique was used to select households' representatives' samples. Characteristics such as institutional factors, sales, socio-economic characteristics, household sizes, and outputs were used to divide the farmers into groups in each site. The DAFF surveys covered random samples of about 4,286 rural smallholder farmers in four provinces of the country. However, this study has only focused on two of the provinces, namely Mpumalanga and Limpopo, with a total of 1,520 respondents selected.

Methods of Data Analysis

The most used econometric analytical techniques in the analysis of crop market participation include Tobit models, double-hurdle models, and Heckman sample selection models (Donkor et al., 2018; Chen et al., 2020; Tafesse et al., 2020). The Heckman approach is more suitable for incidental truncation where the unobserved values are represented by the zeros; for instance, in situations of wage rate models where the unemployed people are included in the sample (Heckman, 1976; Cameron and Trivedi, 2005). This study used the double-hurdle model, which has been used by many previous studies to analyze the determinants of market participation (Reyes et al., 2012; Achandi and Mujawamariya, 2016; Ingabire et al., 2017).

The double-hurdle model is a two-step decision model: (1) the household decides whether or not to participate in the indigenous crop market and (2) the household decides on the volume of indigenous crops to be marketed. The double-hurdle model (DHM) is known to be a corner solution outcome in dealing with issues of agricultural commercialization of smallholder farmers. This model allows for two types of zero: always zeros, and corner solutions (so that participants have to overcome two hurdles instead of one to sell a positive quantity). It was perfect for this study because it estimates unbiased, efficient and consistent parameters following numerous studies that have applied it (Komarek, 2010; Mather et al., 2013; Achandi and Mujawamariya, 2016). Also, it does not require the participation decision and the participation intensity to be determined in the same process. In the first stage of the double-hurdle model, values of 1 and 0 are assigned to represent the choice of the smallholder farmer's decision on whether to commercialize the produce or not. Then in the second stage, the factors that determine the extent of commercialization of indigenous crops sold to the market were analyzed using a fractional response model with quasi-maximum likelihood.

A smallholder farmer's decision to participate in indigenous crops marketing can be represented by:

$$Market\_Part_i^* = x_i\beta + e_i \tag{1}$$

Where $\boldsymbol{Market\_Part_i^*}$ is the latent variable that indicates whether or not the farmer participates in the market (sells the crops), x is a vector of observed independent covariates explaining the decision of market participation, β is an unobserved parameter that is to be estimated and e_i is an unobserved error term capturing all other factors, and $e_i N(0,1)$.

$$MARKET\_PART_i = \begin{Bmatrix} 1\ if\ Y_i^* > 0 \\ 0\ if\ Y_i^* < 0 \end{Bmatrix} \tag{2}$$

$MARKET\_PART_i$ is positive $MARKET\_PART_i = 1$ if a farmer effectively participates in the selling of crop (as a seller), i.e. $Market\_Part_i^* > 0$, and $MARKET\_PART_i = 0$ or negative if a farmer i chooses not to or does not sell in the market. Y_i^* is the quantity of crops sold by smallholder farmer i Conditional to market participation decision.

TABLE 2 | Estimated factors that affect the smallholder farmers' decisions for market participation.

Variable name	Variable definition	Variable type and measurement	Market participation effect
Age	Age of the household head	In years (continuous)	±
Gender	Gender of the household head	Dummy (1 = male, 0 = female)	+
Marital status	Marital status of the household head	Marital status (1 = married, 0 = single)	
Household size	Number of members of the household	Size of household (continuous)	–
Educational attainment	Education level of the household head	Education level (continuous)	+
Livestock	Ownership of livestock	Dummy (1 = yes, 0 = no)	±
Distance	Distance to the market	In kilometers (continuous)	–
Credit access	Access to credit	Dummy (1 = yes, 0 = no)	+
Extension services	Access to extension service	Dummy (1 = yes, 0 = no)	+

± indicates whether the hypothesized effect will be positive or negative, + indicate a positive estimated effect, and – indicate the negative estimated effect.

In accurate terms, the probit model in stage one of assessment is expressed as:

$$\Pr\left(MARKET\_PART_i\right) = X_0 + X_1\beta_1 + X_3\beta_3 \ldots X_n\beta_n + e \quad (3)$$

Where $\Pr\left(MARKET\_PART_i\right)$ is a smallholder farmer's probability of settling to participate in the market in the form of selling their produce or not, X_0 is a constant parameter, whereas $X_1 \ldots X_n$ are parameters are to be estimated, $\beta_{1\ldots}\beta_n$ are identified in **Tables 1** and **2** respectively as the vector of explanatory variables, e represents an error term.

From the probit model of the first hurdle, the Inverse Mills Ratio (IMR) is predicted and included as a regressor in the second stage (second hurdle). This is done purposefully to control the selection bias to obtain unbiased, consistent as well as efficient estimators using ordinary least squares. The IMR equation is expressed as follows:

$$\frac{\phi\left[\nu\left(\frac{P_i}{\alpha}\right)\right]}{\phi\left(P_i\alpha\right)} \quad (4)$$

Where ϕ denotes the normal probability density function. Following is the second-stage equation:

$$E = Y/Z = f\left(x_i\beta_i\right) + e\frac{\phi\left[\nu\left(\frac{P_i}{\alpha}\right)\right]}{\phi\left(P_i\alpha\right)} \quad (5)$$

Where E denotes the assumption operator, Y representing the (continuous) extent of the vegetables sold in the market, x influences the volume of the vegetables sold and is known as the vector of independent variables, and β is said to be the vector of the comparing coefficients to be assessed.

In the second hurdle, the study employs the method recommended by Papke and Wooldridge (1996). A fractional response model was employed to estimate the level of commercialization while taking into account the type of dependent variable. The generated sample selection term IMR from the probit model (first hurdle) was fitted as an exogenous variable to account for potential selectivity bias in the fractional response model regarding the level of commercialization (Wooldridge, 2012). The second stage (level of commercialization) equation is expressed as:

$$E(HCI_i/MARKET\_PART_i = 1) = f(P_i, \beta) + \omega\lambda \quad (6)$$

$$E(HCI/X_iHCI > 0) = \alpha(X_i\Psi) + \omega\lambda \quad (7)$$

where HCI is the observed response on the level of commercialization (HCI)[1], E is the expectation operator; P_i is a vector of the household characteristics; β is a vector of parameters to be estimated; λ is the IMR which accounts for sample selection bias in the probit model, and ω is the associated parameter to be estimated.

Following Cardoso et al. (2010), assumptions of independence and dominance of the double-hurdle model entered multiplicatively into the log-likelihood function. This allows the two parts of the DH model to be estimated separately: the participation process by a probit regression model while the second hurdle was estimated with the aid of fractional logit QML estimation approach on the sub-sample of positive observations of HCI with the Inverse Mills Ratio used as a regressor in the estimation for correcting selection bias.

The Household Commercialization Index (HCI) was useful in the analysis of the level of indigenous crop output marketed by the smallholder farmers. This is a tool that is used to determine the specific level of commercialization that each household contributes to the market. The most frequently used method of measuring agricultural commercialization in the literature is the proportion of the value of crop sold concerning the value of crop harvested (Chukwukere et al., 2012; Ochieng et al., 2016; Nwafor and van der Westhuizen, 2020). The index can be expressed as follows:

$$HCI_i = \frac{Gross\ value\ of\ crop\ sales\ hhi\ year\ j}{Gross\ value\ of\ all\ crop\ production\ hhi\ year\ j} \times 100 \quad (8)$$

The index measures the ratio of the gross value of indigenous crop sales by household i in year j to the gross value of all indigenous crops produced by the same household i in the same year j expressed as a percentage. The index measures the extent to

[1] *The outcome variable for the second hurdle, level of commercialization, is the HCI index from the indigenous farmers in the study area.*

TABLE 3 | Distribution of all the indigenous crops grown by smallholder farmers.

Indigenous crops	Indigenous crop farmers in the Mpumalanga and Limpopo provinces	
	Frequency	Percentage
Sorghum	1	0.5
Pumpkin	75	36
Okra	4	1.9
Millet	3	1.4
Leafy vegetables	63	30
Eggplant	4	1.9
Cowpea	4	1.9
Cassava	4	1.9
Bambara groundnut	15	7
Amadumbe	36	17

TABLE 4 | Distribution of all indigenous crops that were sold to the market by smallholder farmers.

Indigenous crops	Smallholder indigenous farmers participating in the market	
	Frequency	Percentage
Sorghum	1	2.4
Pumpkin	8	20
Okra	2	5
Millet	0	0
Leafy vegetables	15	37
Eggplant	0	0
Cowpea	0	0
Cassava	2	5
Bambara groundnut	3	7
Amadumbe	10	24

which household indigenous crop production is oriented toward the market. Thus, a value of zero would be an indication of a subsistence-oriented smallholder farmer whereas the closer the index is to 100, the higher the degree that the smallholder farmer is market-orientated (Hailua et al., 2015). The advantage of this approach is that commercialization is treated as a continuum thereby avoiding a crude distinction between "commercialized" and "non-commercialized" households.

RESULTS

Demographic and Socioeconomic Characteristics of the Household Involved in the Production and Marketing of Indigenous Crops

This sub-section of this study presents the demographic and socioeconomic features of the respondents, from a sample of 1,520 rural households. The study found these features to be of great assistance in the matter of distinctly portraying the respondents' diverse backgrounds and the impact diversity has had on the descriptive, statistical, and econometric results. The results revealed that out of 1,520 smallholder farmers that participated in the study, about 209 were involved in the production of the indigenous crops. Out of 209 smallholder indigenous farmers, about 41 were involved in the commercialization of the identified indigenous crops (**Table 1**). As presented in **Table 3**, the mostly produced indigenous crop was pumpkin (36%), followed by leafy vegetables (16%). The least (0.5%) produced indigenous crop was sorghum. This could be as a result of sorghum not being popularly consumed as food but mainly used as an ingredient in the production of traditional beer.

Table 4 showed the different indigenous crops sold by smallholder farmers. As represented in **Table 4**, the results showed that leafy vegetables were the most sold indigenous crops compared to the other crops. It was also revealed that indigenous crops such as millet, eggplant and cowpea were not commercialized. A possible explanation for this could be the fact that the crops were not enough for both consumption and selling. While pumpkin was found to be the most grown indigenous crop, the extent of its commercialization was limited, suggesting the need to encourage smallholder indigenous crop farmers to participate in the market.

The result of the *t*-test as shown in **Table 5**, revealed that the smallholder indigenous crop farmers' mean age and education were not significantly different among the market participants and non-participants. As represented, the mean age for smallholder farmers that participated in the market was 47.33 years, whereas the ones that did not participate in the market had a mean age of 44.23 years. Furthermore, the mean number of years of education for market participants was 9.16 as compared to the non-participants with an average of 5.44 years of formal education. This implies that the literate farmers could at least read, write and hold conversations about commercial farming. Also, they had greater opportunities in terms of taking their farming ventures into other levels of success, including having more international market access than the illiterate ones. The mean output of indigenous crops together with market participation had a significant difference ($P < 0.05$). From the results, at least 800.69 kg was the average yield that was harvested specifically for market participation, whereas only 200.17 kg represented those that did not participate in the market. The higher market yield for participant farmers meant that they had the privilege of consuming and selling at the same time. Amongst all the other tables of this study with demographic characteristics of smallholder farmers in Limpopo and Mpumalanga, South Africa, **Tables 5**, **6** present various means and standard deviations.

The Distributions of Commercialization Level of Indigenous Crops

According to Strasberg et al. (1999) the household commercialization index (HCI) measures the extent to which indigenous vegetable production gravitates toward the market. The index indicates variations in the level of indigenous

TABLE 5 | Demographic characteristics of smallholder farmers that were involved in the production of indigenous crops in Limpopo and Mpumalanga provinces, South Africa.

Characteristics	Market participation	Mean	*F*-value	Degrees of freedom	*P*-value
Age of the household head	Yes	47.33	1.009	129	0.314
	No	44.23		21.52	
Education of the household head	Yes	9.16	0.000	102	0.989
	No	5.44		17.14	
Total output of the indigenous crops (KG)	Yes	800.69	26.623	318	0.000***
	No	200.17		132.00	

****, **, * Indicate significance at 1, 5, and 10% level, respectively.*

TABLE 6 | Demographic characteristics of indigenous crops' farmers in Limpopo and Mpumalanga provinces, South Africa.

Variables	Market participants		Non-market participants		Pooled	
	Mean	Standard deviation (SD)	Mean	Standard deviation (SD)	Mean	Standard deviation (SD)
Gender of the household head	0.564	0.112	0.533	0.100	1.27	0.45
Household age (Years)	47.333	13.342	44.443	12.666	49.12	11.89
Marital status	0.465	0.356	0.443	0.344	4.21	2.44
Household size (Numbers)	4.786	1.223	3.889	1.012	4.93	2.71
Educational level of household (Years)	6.678	3.048	5.423	2.345	33.58	40.30
Ownership of livestock	0.587	0.357	0.700	0.327	1.77	0.42
Distance to the market (Km)	0.487	0.356	0.475	0.245	1.86	1.82
Access to market information	0.573	0.785	0.455	0.676	1.94	0.24
Access to agricultural assistance	0.486	0.345	0.428	0.367	1.92	0.27
Family member with HIV	0.444	0.432	0.378	0.421	0.47	0.79
Family member worked on farm	0.655	0.557	0.544	0.447	0.98	0.76
Social grant	0.468	0.367	0.490	0.455	1.99	0.73
Irrigation type	0.586	0.234	0.354	0.345	1.52	0.50
Total output of indigenous crops (kg)	800.69	671.8	200.17.2	6.74	1000.22	768.067

vegetable commercialization across the study area. Households were divided into three categories of equal size according to their HCI. As shown in **Figure 1**, different levels of indigenous crops commercialization among the farmers in the study area are revealed. The results of **Figure 1** show that half of the farmers (51%) are still operating almost at the subsistence level. In the same vein, a large number (31%) of the farmers are still at low-medium levels while the rest (18%) are high-level market participants.

While estimating the double-hurdle with the Quasi-maximum likelihood fractional response model, the covariates included in the models were tested for multi-collinearity using the variance inflation factor (VIF). An average VIF of 2.17 shows that the multi-collinearity problem is not an issue among the covariates used for the study. The probit model (first hurdle) was used to estimate factors influencing the commercialization of indigenous crops among the respondents in the study area. The results are shown in **Table 7**, where the first-hurdle model of the double-model revealed that only the salary of the household and agricultural information was significant at the 1% level. Surprisingly, education had not only no significant impact to the smallholder farmers commercializing their produce, but also it had an unexpected negative coefficient.

From the Probit results, the gender of the household head had a positive effect, at a 5% level of significance, on the determinants of the commercialization of indigenous crops. The results showed that off-farm income had a positive impact, and statistically significant at the level of 5%. Furthermore, the results revealed that if a household member was HIV positive that had a negative effect on the market participation of the farmer with a 10% level of significance. The results show that a household with a member infected with HIV is likely not to participate in the market.

The Determinants of the Commercialization Level of Indigenous Vegetable Production: A Quasi-Maximum Likelihood Estimates Fractional Logit Model

The results on factors influencing the level of commercialization among indigenous vegetable farmers are as presented in **Table 8**. The variable household size, gender, marital status, access to information, access to extension, and disability grant were statistically significant and discussed. To correct for selectivity bias, an inverse mill ratio (IMR) was used as a covariate in the model (second hurdle). The IMR was not statistically significant which shows that bias due to selection was not a problem. Hence, using a double hurdle model for estimating determinants and level of commercialization is justified. From the second-hurdle equation it was revealed that the household size, gender of the household head, marital status, access to extension as well as the disability grant were all statistically significant.

The results show that the household size had a positive influence on the level of participation of smallholder farmers with statistical significance of level 10%. Contrary to the first-hurdle model, the coefficient of gender of the household head was negative and statistical significant in influencing market participation. The results also revealed that both marital status and access to information were statistically significant at level 5%, even though their coefficients were opposite (marital status had a positive coefficient whereas access to information had a negative coefficient). It was also revealed that the number of indigenous crops sold in the market was positively influenced by the access to extension services, with a 1% of significance level. This study showed that the disability grant had a negative impact on the level of participation to the market by smallholder farmers with the significance level of 10%.

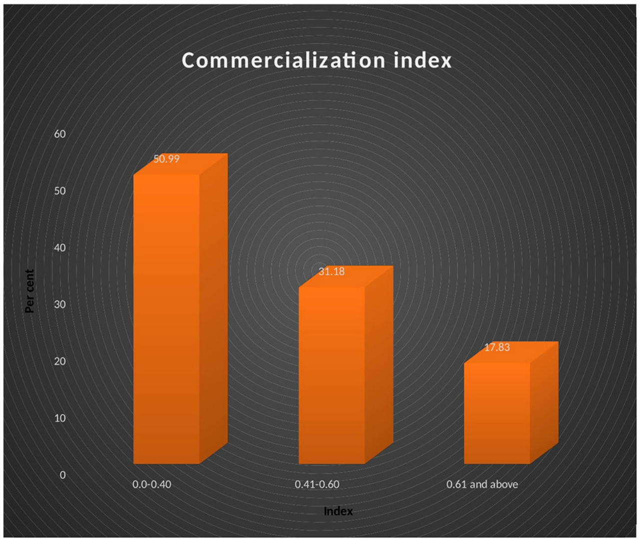

FIGURE 1 | Distribution of the commercialization index of indigenous crops.

DISCUSSION

The objective of the study was to determine the factors influencing the extent of commercialization of indigenous crops among smallholder farmers.

TABLE 7 | Probit results for determinants of commercialization of indigenous crops.

Commercialization	Coef.	St.Err.	*p*-value	dy/dx	Std.Err.	*P*-value
Household size	0.016	0.049	0.740	0.000	0.001	0.740
Gender of the household head	0.849	0.358	0.018**	0.012	0.005	0.018**
Residents of household	−0.092	0.704	0.896	−0.001	0.010	0.896
Educational level	−0.236	0.721	0.744	−0.003	0.011	0.744
Marital status	0.188	1.272	0.882	0.003	0.019	0.883
Agricultural information	2.057	0.564	0.000***	0.030	0.008	0.000***
Involved in livestock prod	−0.511	0.613	0.405	−0.007	0.009	0.404
Off–farm income	1.037	0.418	0.013**	0.015	0.006	0.013**
WEALTHINDEX[a]	1.139	0.260	0.000***	0.017	0.004	0.000***
Access to extension	−0.274	0.334	0.412	−0.004	0.005	0.410
Access to the disability grant	−0.427	1.293	0.741	−0.006	0.019	0.741
Household member with HIV	−1.000	0.542	0.0658*	−0.015	0.008	0.062*
Constant	0.152	0.996	0.878			
Mean dependent var	0.646					
Pseudo r-squared	0.957					
Chi-square	1824.810					
Akaike crit. (AIC)	107.636					
SD dependent var	0.516					
Number of obs	1454.000					
Prob> chi2	0.000					
Bayesian crit. (BIC)	176.303					
VIF	2.17					

[a]*WEALTHINDEX was generated using principal component analysis (PCA) from the list of wealth indicators owned by the indigenous vegetable farmers. The lists are: wall materials of the house, bank account, owning vehicles, owning a TV, owning radio, type of ceiling, the main fuel used for cooking, etc.*
****, **, * Indicate significance at 1, 5, and 10% level, respectively.*

TABLE 8 | Determinants of the extent of commercialization of indigenous crops (Quasi-maximum likelihood estimates fractional logit model).

Commercialization index	Coef.	Std.Err.	*P*-value
Household size	0.014	0.008	0.091*
Gender of household head	−0.192	0.108	0.077*
If the household head resident	−0.224	0.215	0.298
Education of household head	0.124	0.226	0.584
Marital status	1.034	0.459	0.024**
Access to information	−0.200	0.094	0.033**
If_HH_involved_in_livestock_prod	−0.107	0.261	0.681
If_member_worked_for_a_wage_salary	−0.206	0.182	0.257
WEATHINDEX	0.168	0.105	0.111
HH_received_advice_from_government	−0.043	0.098	0.659
Access to extension	0.085	0.048	0.078*
Disability grant	−0.888	0.464	0.056*
HIV_if_a_member_has_been_informed	−0.359	0.226	0.112
Inverse mills ratio (IMR)	0.040	0.113	0.724
Constant	0.513	0.406	0.206
Wald chi2(14	30.73		
Prob> chi2	0.0061		
Pseudo R2	0.0060		
Log pseudo-likelihood	−976.31617		

****, **, * Indicate significance at 1, 5, and 10% level, respectively.*

The Factors That Influence the Smallholder Farmers' Decision to Participate in the Market

The positive coefficient sign in the gender of the household head implies that gender plays a huge role in the commercialization of indigenous crops. It also provides a clear implication that when men and women work together, they achieve a positive outcome. Sebatta et al. (2014) asserted that men hold the responsibility of deciding whether to participate in the market or not and how much. On the other hand, women become more active in the marketing of arable crops. However, the results of this study differ from what Hill and Vigneri (2014) found in their study as they reported that men practice cash crops farming for the sake of taking care of their families, whereas women produce crops mainly for consumption purposes. This implies that they do not work together in the production of indigenous crops.

Gaining access to information is a key factor that mostly influences farmers' decisions to participate in the marketing of a product. Farmers with access to information can make informed decisions concerning production, crops to grow, and marketing-related information (Dlamini-Mazibuko et al., 2019). Access to information offers farmers the opportunity to make proper decisions relative to favorable product prices and transaction costs (Key et al., 2000). Having access to market information plays a huge role in the decision-making process of the farmers, about how much to sell and on which market. Farmers require such information to make the appropriate decision on the quantity of produce to market and the price to charge and also to have an idea of the market competition. As revealed from the result of this study, access to marketing information has a positive and statistically significant influence on commercialization among indigenous vegetable farmers. The result of this study aligns with the study of Dlamini-Mazibuko et al. (2019) who, in their study on factors affecting the choice of marketing outlet selection strategies by smallholder farmers in Swaziland, found a positive influence of market information, on the decision to participate in the market.

The positive coefficient implies that the involvement of indigenous crop farmers in off-farm income opportunities increases their likelihood of commercializing indigenous crops. This implies that regardless of households' other means of making income, they still manage to produce crops and participate in the market. Usually, households that have other means of making income are business-minded and can multitask. Other than farming, females always get involved in other streams of generating income, especially in female-headed households. They partake in casual jobs to take care of their families' needs. The results of this study corroborate that of Mthembu (2013) who from their findings showed that women were not only involved in the production and marketing of indigenous crops, but also worked as road maintainers, with others sewing and making grass mats.

The negative coefficient result indicates that a household with a member infected with HIV is likely not to participate in the market. This could be attributed to the fact that farmers tend to spend more time taking care of the sick and less time trying to make produce. From the study conducted by Khapayi and Celliers (2016), having a sick member could reduce labor which negatively impacts the decision to participate in the market because smallholder production depends highly on family labor in the production of crops. This result is consistent with Adenegan and Adewusi (2007) who concluded that if the number of HIV-infected households increases in the rural areas then their survival strategies together with food security get threatened as well.

The Determinants of the Level of Market Participation of Smallholder Farmers

The coefficient of access to extension had a statistically positive influence on the household level of commercialization. This study aligns with the study of Ojo and Baiyegunhi (2020) who found a positive relationship between access to extension service and the farmers' choice of the adoption of a climate change adaptation strategy. Extension services improve the understanding of farmers, which leads to higher production, a higher probability of participating in the market, and the commercialization of indigenous crops. The results of this study comply with the study of Martey et al. (2012) who indicate that the extent of commercialization is determined by farmers' access to extension service. Therefore, the importance of providing timely access to extension services would significantly contribute to how farmers make their decisions when planning to commercialize the production and marketing of indigenous crops.

The positive coefficient illustrates that as the number of household members increases, so does the quantity sold in the market. These results are in contrast with what Kyaw et al. (2018) reported. In their findings, they discovered that the size of the household had a negative impact and it was statistically significant. It was then concluded that large households are associated with fewer agricultural products to sell in the market due to prioritizing the consumption needs of the household. The findings were substantiated by Siziba et al. (2011) who posited that the larger the number of households in the family the lesser the chances of them marketing the quantity that is beyond their consumption satisfaction.

The coefficient of gender of household head was negatively signed and statistically significant. It was no surprise that the results came out negative, and this is mainly because female-headed households are more likely to be involved in the market of indigenous crops as compared to the male counterparts who mostly involved in the harvesting and marketing of cash crops. The result is in tandem with other studies conducted by Shackleton and Shackleton (2006) and Avocèvou-Ayisso et al. (2009) in South Africa and Nigeria, respectively. This study found the gender of the household head to be a significant determinant in marketing of indigenous crops. In the same vein, the findings of Sinyolo et al. (2017) revealed that female-headed households sold more quantities of maize than male-headed households. However, the results of this study were in variance with those of the past numerous studies (Boughton et al., 2007; Hlongwane et al., 2014; Sigei et al., 2014) who posited that female-headed households not only lack extension services but also suffer from limited information access on trends and the inability to secure greater contracts that could help provide them with better markets for their crops.

Contrary to the first hurdle, access to market information indicated a negative impact on the volume of the indigenous crops to be sold in the market. The result shows that the more the indigenous crops farmers has access to the market information, the volume offered for sale reduces. This is unexpected from the economic point of view. However, the plausible reason could be attributed to inadequate or unqualified staff members and poor organization, which could limit the efficient dissemination of market information (De et al., 2005; Ojo et al., 2019; Bello et al., 2020). As a result, market information might not be disseminated as efficiently as expected. This could be the fact that most indigenous crop farmers reside in remote areas with a lack of good quality infrastructure, skills in agricultural activities, and inadequate storage facilities and transport (Minot and Sawyer, 2016). This not only impedes their opportunity for competing in the international markets but also deprives them of the opportunities of earning a living through the commercialization of indigenous crops. Also, this infers that being unable to sell their produce, smallholder farmers could end up not partaking in the agricultural sector at all.

The positive relationship between the access to extension services and farmer's commercialization of indigenous crops implies that having access to extension services provides the smallholder farmers with the privilege of being aware of market availability. It also comes in handy in enhancing their knowledge of production by making them aware of information on improved varieties. These results manifest the importance of the urgency of implementing not only improved technology but also support services in the promotion of market sales. Apind et al. (2015) found similar positive results to this study specifying that the extension services had a positive coefficient and significantly influenced the volume of rice that the smallholder farmers sold in the market. Alemu et al. (2012) added that the access to extension services in Ethiopia increased the probability of smallholder farmers opting for the contract market rather than settling for the spot market.

The negative coefficient on disability grants implies that the rise in the income of households that receive the disability grant may entrench an entitlement and culture of dependency among them. This could result in them being lazy or even not growing crops, let alone engaging in income-generating ventures. Similar findings were also reported by Aliber and Hall (2012) and Tirivayi et al. (2016). However, not participating in the market could also be due to the physical condition of the smallholder farmer.

CONCLUSION AND RECOMMENDATIONS

The participation of smallholder farmers in marketing of produce can play a critical role in meeting their goals such as food and nutrition security, poverty alleviation and sustainable agriculture. This study found that the market participation and sales ratio of smallholder indigenous crop farmers are constrained by numerous factors, such as socioeconomic, market and institutional factors. The commercialization of the indigenous crop for smallholder farmers in the market was affected by gender, educational level, off-farm income, agricultural information, and a member being infected by HIV. The household size, gender of household head, access to market information, extension services and disability grant were found to highly influence the extent of commercialization among the smallholder indigenous vegetable farmers.

To fully realize the optimum contribution of indigenous crops to household food and nutrition security, support from the stakeholders must be geared toward the smallholder indigenous farmers through the provision of farm training for an effective and efficient grasp of agricultural and marketing information. To improve smallholder farmers' access to markets, government also needs to ensure that their support for the production of indigenous crops is timely and well-targeted in order to upscale its production for consumption and commercialization. Where possible, government and other stakeholders need to channel their support through organized cooperatives that exist within the smallholder farmers. Much attention and support need to be given to women's involvement in market participation, and they also need to be empowered by the government and other interested stakeholders to participate fully in the decision making relating to the price of their produce and where to sell it. More workshops especially for young people and women need to be conducted in rural areas to raise awareness on the nutritional importance of indigenous crops and the need to include these indigenous crops into South Africa's dietary guidelines.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: This dataset belongs to the South African Vulnerability Assessment Committee (SAVAC), hosted by the Department of Agriculture, Land Reform and Rural Development (DALRRD). If you want it you apply from SAVAC. Requests to access these datasets should be directed to the website for DALRRD, www.dalrrd.gov.za.

AUTHOR CONTRIBUTIONS

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

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Can Digitalization Levels Affect Agricultural Total Factor Productivity? Evidence From China

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The agricultural sector faces a food crisis and major challenges in green and sustainable development, and digital technology is an important countermeasure. In this paper, "digital technology" is used as a keyword to construct a regional digitalization level indicator. China's provincial panel data from 2013 to 2020 are adopted as samples to explore the impact of regional digitalization levels on agricultural total factor productivity and its mechanism. The study found the following: (1) Regional digitalization can significantly raise agricultural total factor productivity. (2) Regional digitalization can significantly raise agricultural total factor productivity in economically underdeveloped areas but not in economically developed areas. (3) The mitigation of factor market distortion and large-scale production can strengthen the role of regional digitalization in raising agricultural total factor productivity.

Keywords: digitalization level, agricultural total factor productivity, factor market distortion, large-scale production, heterogeneity

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INTRODUCTION

In order to cope with the food security issue brought about by population growth, government, and researchers have focused on the efficiency of agricultural production. Improving agricultural total factor productivity not only is a key way to solve the problem of global food security but also can advance the agricultural sector and the overall economy by adjusting the allocation of labor (Cao and Birchenall, 2013; Ball et al., 2015). It is particularly important for the economic growth of poor countries or regions (Fuglie, 2018). However, the agricultural production in economically developed regions such as the United States and Europe is slowing down. Although the growth rate of agricultural total factor productivity in developing countries such as China is relatively high (Alston and Pardey, 2014), extensive growth impacts the ecological environment, leading to issues such as excessive fertilization, forest destruction, and water pollution (Ju et al., 2009; Schwarzenbach et al., 2010; Laurance et al., 2014). As such, the transformation of the agricultural production model is imminent. The digital transformation of agriculture reduces the use of chemical products, saves water resources, and increases per unit output and environmental sustainability. It is another technological upgrade following agricultural mechanized production. With the emergence of digital technology, global agriculture faces restructuring and transformation. Digital technology is a strong driving force for environmentally friendly and sustainable agricultural growth.

Digitization is the social technological process of applying digital innovation (Klerkx et al., 2019). Emerging technologies such as big data, the Internet of Things, and artificial intelligence not only have a great impact on the business economy (Chen et al., 2012; Ng and Wakenshaw, 2017) but also will reshape traditional agricultural production. Agricultural digitalization is to integrate advanced digital technologies such as artificial intelligence, big data, and robotics and connect these digital technologies to agricultural production systems through the Internet of things (Lioutas et al., 2021). In addition, digital technology will also play a role in the entire agricultural production chain (Shepherd et al., 2020). Digital technology will gradually become a part of the agricultural production infrastructure. Although it can have a positive effect on agricultural production efficiency, high investment costs and the digital divide between technology adaptors limit the widespread adoption of agricultural digital technology (Benyam et al., 2021). Under these circumstances, government investment in digital construction not only helps popularize digital production technology to farmers but also improves the digital and intelligent levels of the external environment and promotes the deep integration of digital technology with the agricultural real economy. As a result, the agricultural production process and the circulation of elements in the value chain will be optimized, the "digital divide" will be narrowed, and the cost for laborers to adapt to digital technology will be reduced, thereby increasing the agricultural total factor productivity and ultimately pressing ahead with agricultural green and sustainable production.

This study explores the impact of digitalization levels on agricultural total factor productivity through the establishment of a fixed-effect model of provincial samples, and further determines the causal relationship between regional digitalization levels and agricultural total factor productivity through IV-GMM method. The study has found that the overall digitalization of a region not only promotes the digital transformation of agricultural production but also effectively improves market information communication and value chain element circulation, thereby increasing agricultural total factor productivity. The heterogeneity test results show that, in economically underdeveloped areas, digitalization can significantly increase agricultural total factor productivity. In addition, alleviated distortion of market factor allocation and large-scale production can positively enhance the promotion effect of regional digitalization level on agricultural total factor productivity. We believe that digital development is an effective means for countries to transform agricultural production and improve agricultural production efficiency.

The theoretical contributions of this paper mainly include: First, an indicator is developed to measure regional digitalization levels based on the Internet big data search engine. To study the effect of China's digital construction, the level of digitalization must be measured. However, the lack of measurement research on this indicator hinders the development of related theories. The paper measures regional digitalization levels based on the number of keyword searches related to digital technology in prefecture-level cities or municipalities in Baidu News, which provides a reference for subsequent research on digitalization. Second, the impact on agricultural total factor productivity is analyzed from the overall perspective of regional digital construction, breaking the shackles of the current research framework. Previous empirical studies on agricultural total factor productivity are often limited to the impact of input factors or agricultural policies, including natural conditions (Liang et al., 2017), farm size (Rada and Fuglie, 2019), R&D expenditure (Fuglie, 2017), agricultural subsidy policy (Rizov et al., 2013), and agricultural trade policy (Yoo et al., 2012), while this paper incorporates the regional digital environment into the analysis framework, with the focus on the overall environment of agricultural production with government participation, which contributes to the understanding of emerging production technologies and factors affecting agricultural total factor productivity, and enriches the literature on the effect of regional digital development and studies on the growth factors of agricultural total factor productivity.

At a practical level, the impact of digitalization levels on agricultural total factor productivity is analyzed from the perspectives of market factor allocation, large-scale production, and the heterogeneous results caused by differences in economic development levels. The analysis shows that regional digitalization can significantly increase agricultural total factor productivity, especially in regions with lower levels of economic development. In addition, an increase in the efficiency of factor allocation in the external market and a commitment to large-scale production will strengthen the role of regional digitalization in raising agricultural total factor productivity. This provides useful empirical evidence for the government to promote the deep integration of digital construction and agricultural production.

The remaining part of this paper is structured as follows: The second part is the research plan, which elaborates the mechanism of the impact of regional digitalization on agricultural total factor productivity, empirical model construction, data sources, and variable selection and conducts a descriptive statistical analysis. The third part contains the econometric test, endogenous treatment, and robustness test of digitalization on agricultural total factor productivity and analyzes the heterogeneity of the economic development level and the adjustment mechanism of factor configuration distortion and large-scale production. The fourth part provides conclusions and recommendations.

RESEARCH PLAN

Research Hypothesis

Regional digitalization promotes the optimization of the entire process of agricultural production through agricultural digital technology, thereby increasing the agricultural total factor productivity. Agricultural digital technologies such as big data and the Internet of Things help control agricultural production and improve agricultural efficiency (Wolfert et al., 2017). Food traceability technology derived from blockchain and Internet technology can manage food safety issues, improve the transparency of supply chains, and advance sustainable development (Creydt and Fischer, 2019; Kamble et al., 2020). Information and communication technology can help increase the efficiency of resource use in food businesses as well as the productivity of pesticides and fertilizers (Radoglou-Grammatikis et al., 2020). Technologies such as artificial intelligence, smart robots, and the Internet of Things form smart water conservancy technologies that help the effective use of agricultural water resources (Muangprathub et al., 2019). These technological advances enable the effective use of resources and the improvement of agricultural total factor productivity.

The role of digitalization in raising agricultural total factor productivity is also reflected in optimizing the external market environment and improving agricultural policies. George (George, 2014) pointed out that agricultural total factor productivity in developing countries has increased through investments in irrigation and machinery, but crop production in these countries still lags behind in terms of the progress of agronomy. The important reason behind this is that farmers in developing countries who are poorly educated and risk-averse prefer low-risk, low-return production methods. On top of that, information asymmetry in product markets further locks agricultural growth potential. The asymmetry of agricultural market information leads to abnormal fluctuations in agricultural product prices and sales, which may mislead farmers in planting and production decisions, increase the probability of loss, and affect agricultural output value, reducing agricultural total factor productivity. Therefore, digital construction, mobile Internet, and information sharing can reduce the information asymmetry between agricultural producers and external markets (Lin et al., 2013; Deichmann et al., 2016), thereby creating a low-risk, high-return external market environment and securing stable or predictable market prices and sales. In addition, Otsuka et al. (2016) pointed out that improper agricultural policies have led to distortions in the Japanese market, the loss of agricultural comparative advantages, and reduced large-scale production efficiency in farms. Big data, the Internet, cloud platforms, and other technologies can improve government transparency and public participation. This ensures a successful implementation of policies, timely feedback, and an effective evaluation of the effects of agricultural policies, thereby improving the implementation effects of agricultural policies. In addition, modern technologies such as big data, blockchain, and mobile communications can improve regional digitalization levels and effectively optimize the agricultural production value chain system and the circulation of resource elements, thereby reducing the distortion of market element allocation and promoting agricultural innovation by drastically reducing transaction costs (Deichmann et al., 2016). Based on the above analysis, the following hypothesis is proposed:

Hypothesis 1 (H1). The regional digitalization level is positively correlated with agricultural total factor productivity.

Generally speaking, the situation of regional agricultural production is in line with the level of economic development. Some studies have compared changes in agricultural production efficiency in countries with different levels of development (Alston and Pardey, 2014; Fuglie, 2018). The conclusion of these studies is that the growth of agricultural total factor productivity in economically developed areas is slowing down, while agricultural total factor productivity in developing countries increases relatively fast. These studies show that differences in the level of economic development have an important impact on the agricultural total factor productivity. Santangelo (2018) analyzed foreign land investment in developed and developing countries and found that governments and investors in developed countries pay more attention to the sustainable development of agriculture and the use of advanced technologies to increase the food production of the investees. However, the governments of developing countries usually require investors' goals to be consistent with national interests and government policies. Therefore, investors in developing countries make less responsible investments, which leads to an excessive use of water, pesticides, and fertilizers. This shows that differences in the level of economic development directly affect the behavior of governments and agricultural investors; for example, they have completely different attitudes toward the use of digital technology. The long-term imbalance of economic development in China may mean that underdeveloped regions pay more attention to the input of pesticides, fertilizers, and agricultural machinery, while economically developed regions pay more attention to green and sustainable digital technologies. In addition, the degree of market information asymmetry in regions with different levels of economic development also differs. Information asymmetry in the agricultural market leads to fluctuations in agricultural product prices and trading volumes, which may mislead farmers in their production and planting decisions, leading to losses and reducing agriculture production value and agricultural total factor productivity. As the effect of a rising regional digitalization level on the information asymmetry in the agricultural market differs in regions with different levels of economic development, the impact of rising regional digitalization level on agricultural total factor productivity is also different.

On the other hand, the efficiency of agricultural production in economically developed regions is relatively high, and efficiency growth may have reached a state of convergence. As a result, regional digitalization has a weaker impact on agricultural total factor productivity, or a higher digitalization level is needed to significantly improve agricultural total factor productivity (which means a higher threshold effect value). This means that the effect of digital development on the improvement of agricultural total factor productivity is insignificant temporarily (Zambon et al., 2019). On the other hand, the agricultural production efficiency in underdeveloped regions is relatively low and promises more potential. Therefore, a rising regional digitalization level can optimize the entire agricultural value chain, such as production, market information, and factor circulation, thereby increasing agricultural total factor productivity. Based on this, the following hypothesis is proposed:

Hypothesis 2 (H2). Digitalization levels exert significantly different impacts on agricultural total factor productivity in regions with different levels of economic development.

Factor allocation efficiency is an important factor affecting agricultural total factor productivity. Distortions in the allocation of market factors caused by an underdeveloped market and lagging government supervision or factor market reforms exist in China (Dai and Cheng, 2016). Research on the consequences of market or economic distortions has shown that market distortions lead to a waste of resources (Yin et al., 2018), which means too much input, less output, and a less efficient use of resources brought about by digital technology. Zhu et al. (2011) proved that the distortion of factor allocation significantly reduces the agricultural total factor productivity of China. Reducing distortions in the allocation of market elements can not only alleviates resource waste but also reduces resource redistribution (Dai and Cheng, 2016). The redistribution of labor resources usually means greater costs (Dower and Markevich, 2018). Therefore, reducing the redistribution of resources means reducing the cost of resource allocation. The reduction in resource costs can strengthen the role of digitalization in increasing agricultural total factor productivity. At the same time, the distortion of the labor market limits the ability of labor forces to learn new skills, while digital technology particularly requires the ability to learn and adapt (Kong et al., 2021). Therefore, alleviating the distortion of labor factor allocation will effectively improve the "digital divide" of labor force. In addition, the information asymmetry in the supply chain distorts the capacity allocation among retailers, leading to inefficient capacity shortages and overpricing (Chen et al., 2014). As such, alleviating the distortion of agricultural market factor allocation can also optimize the agricultural production value chain by reducing information asymmetry, thereby enhancing the role of regional digitalization in increasing agricultural total factor productivity.

The scale of farmland also has a significant impact on agricultural productivity. Previous studies have found that there is often an inverse relationship between the scale of farmland and land output or productivity (Feder, 1985; Barrett, 1996; Barrett et al., 2010). The smaller the scale of farmland, the lower the opportunity cost of labor and the cost of labor employment. If agricultural production technology does not bring about increasingly high returns to scale, farmers' enthusiasm for work will reduce, leading to an inverse relationship between farm size and productivity (Barrett, 1996). Digital technologies such as big data, cloud computing, and artificial intelligence will "empower" the supply of raw materials, production, and sales of traditional agriculture. For example, digital production technologies such as intelligent irrigation, intelligent fertilization, and intelligent pest control, as well as digital supply and sales chain technologies such as intelligent logistics, intelligent storage, and intelligent transportation, will greatly increase the return to scale of farmland. On the other hand, large-scale operation can reduce the unit cost of digital technology input, which facilities the acquisition and analysis of big data in agricultural production and the input and application of artificial intelligence technology. Digital technologies such as digital soil maps and intelligent robots can be mainly used for large farms that require substantial investment (Deichmann et al., 2016). Based on this, the following hypotheses is proposed:

Hypothesis 3a (H3a). The lower the degree of distortion in market factor allocation, the greater the promotion effect of digitalization on agricultural total factor productivity.

Hypothesis 3b (H3b). Large-scale production can strengthen the role of digitalization in increasing agricultural total factor productivity.

Research Model

Agricultural Total Factor Productivity Measurement

In this paper, stochastic frontier analysis (SFA) is used to measure the agricultural total factor productivity in various regions of China. Two main methods are used for measuring China's agricultural total factor productivity in the existing literature: parametric and non-parametric methods. The commonly used parametric method is data envelopment analysis (DEA) (Erdem Demirtaş and Fidan Keçeci, 2020), while the widely applied non-parametric method is stochastic frontier analysis (SFA) (Shabanzadeh-Khoshrody et al., 2016). Compared with data envelopment analysis, the advantage of stochastic frontier analysis is that it can fully consider the impact of random factors on the output through parameter estimation, which is more in line with the essential characteristics of agricultural production, and is less sensitive to outliers. Thus, it can reduce the difference between estimated results and actual efficiency levels. Therefore, based on the research of Aigner et al. (1977), Battese and Coelli (1992), the specific form of the model is set as follows:

$$\ln Y_{it} = lnf\left(X_{it}, t; \beta\right) + v_{it} - u_{it},\ i = 1,\ 2, ..., N;\ t = 1, 2, ..., T$$
$$v_{it} \sim N\left(0, \sigma^2\right), u_{it} \sim |N\left(u, \sigma_u^2\right)| \quad (1)$$

In Model (1), Y_{it} represents the output of the i-th decision-making unit in period t; X_{it} represents the input of the i-th decision-making unit in period t; t represents the time trend, reflecting the time variation of technology; $f\left(X_{it}, t; \beta\right)$ represents a specific functional form, β is the input vector parameter to be estimated; v_{it} represents the influence of climate, natural disasters, measurement errors, and other random factors on the agricultural production frontier, and it is assumed to follow a normal distribution; u_{it} is a non-negative random variable, representing the agricultural production efficiency loss of the sample unit, and it is assumed to follow a truncated normal distribution; the agricultural production technical efficiency of the i-th decision-making unit in the t period is $TE_{it} = \exp(-u_{it})$; v_{it} are u_{it} independent of each other. See **Appendix A** for more explanation of the SFA model.

In the choice of the form of specific function $f\left(X_{it}, t; \beta\right)$, a translog production function, which is more flexible than the C-D production function (Coelli and Perelman, 2000), was used. It is widely used in the calculation of agricultural production efficiency. The specific form is as follows:

$$\ln Y_{it} = \beta_0 + \sum_j \beta_j lnX_{ijt} + \beta_t t + \sum_j \beta_{jt} tlnX_{ijt} + \frac{1}{2}\sum_j \sum_l \beta_{jl} lnX_{ijt} lnX_{ilt} + \frac{1}{2}\beta_{tt} t^2 + v_{it} - u_{it} \quad (2)$$

In Model (2), Y_{it} represents the total agricultural output value of province i in period t, X_{it} is the factor input, and j and l represent the jth and lth factor inputs, respectively. We mainly selected land

(S), labor (L), capital (K), and intermediate product input (M) as input indicators.

The Influence of Digitalization Level on Agricultural Total Factor Productivity

The core issue studied in this paper is the impact of digitalization levels in various regions of China on the agricultural total factor productivity. The fixed-effect regression model of the provincial samples is constructed as follows:

$$TFP_{it} = \alpha_0 + \alpha_1 lnDIG_{it} + \alpha_2 Control_{it} + \gamma_t + \delta_i + \varepsilon_{it} \qquad (3)$$

Model (3) is the main regression model of this paper, and the explained variable TFP_{it} represents the agricultural total factor productivity of the province i in the period t, which is calculated by Model (2); the explanatory variable DIG_{it} is the digitalization level of province i in period t; $Control_{it}$ is the control variables of the model, including the installed capacity of hydropower stations, labor quality, effective irrigation area, the share of financial support for agriculture in fiscal expenditure, and per capita GDP; γ_t is the time effect; ε_{it} is the individual fixed effect and the random error term of the model; the coefficient α_1 is the core parameter that this paper focuses on and is expected to be positive. This is to say, digitalization can promote agricultural total factor productivity.

Data Sources, Variable Selection, and Descriptive Analysis

Data Sources

In 2012, the Chinese government proposed to adhere to the road to informatization and agricultural modernization, promote the deep integration of informatization and industrialization, and realize smart governance by using modern science and technology. Since then, various regions in China have been advancing digitalization. The data used in this paper are from 2013 to 2020, and the sample objects are 31 provinces or municipalities in China. The research data come from the China Statistical Yearbook and China Rural Statistical Yearbook. Some data are missing. Since China's agricultural development has been in a state of steady growth (Cao and Birchenall, 2013), we used the average growth rate method to supplement the missing data.

Variable Selection and Descriptive Statistics

(1) Explained variable (TFP). First, with regard to the calculation of agricultural total factor productivity, we selected the total output value of agriculture, forestry, animal husbandry, and fishery as the output index Y. In terms of factor input, the sown area of crops at the end of the year (S) is used in this paper as the index of land input, and the number of employees in the primary industry (L) is used as the index of labor input. In view of the availability of data and reference to the previous literature (Quan, 2009), the total power of agricultural machinery (K) and the consumption of chemical fertilizers (M) are used as alternative input indicators for agricultural capital and intermediate input, respectively. At the same time, in order to avoid the multicollinearity between the high-order terms (quadratic terms and interaction terms) and the low-order terms (first-order terms) in the translog production function as much as possible, as well as the impact of differences in their dimensions, the input and output indexes are standardized in this paper.

(2) Core explanatory variable (DIG). The core explanatory variable in this paper is the digital technology level of 31 provinces or municipalities in Mainland China (excluding Taiwan, Hong Kong, and Macau). The quantitative evaluation of this indicator is a frontier issue that has not yet been involved in the academic community. This paper draws on the practice of Han et al. (2017) to use keywords to count the cumulative number of corresponding industrial policy documents in various provinces and cities as an indicator of industrial policy intensity, and at the same time refers to the idea of Li et al. (2020) to use crawler technology to construct the financial technology development level index based on the number of Baidu news search results. Web crawler technology is used to count the digital-related news volume in prefecture-level cities and above in China to arrive at the digitalization level index of each province and city. Most of the digital construction activities are monitored in various regions of China. The more digital construction activities there are, the greater the amount of relevant news reports. Therefore, the number of relevant news reports represents the digitalization level in each region to a certain extent. News reports on Baidu, the world's largest and most comprehensive Chinese search engine, can be accurately searched by keywords. Therefore, we used Baidu to search for relevant news. Specifically, this paper refers to the "White Paper on China's Digital Economy Development (2020)", "2020 Digital Trends Report," and other research reports, as well as the "14th Five-Year Plan" report, the report of the 19th CPC National Congress, relevant policy documents and news reports of various local governments, and classic literature on Chinese digitization research (Wu et al., 2021) and extracts keywords related to digitization through Python's Jieba word segmentation function. We matched these keywords with prefecture-level cities or municipalities in China, searched for prefecture-level cities or municipalities + keywords, such as "Guangzhou + Big Data" in the Baidu news search, and used web crawler technology to count the search results. The total search volume was obtained by summing up the search volume of all keywords in a prefecture-level city or municipality. Because this kind of data has a typical "right-biased" characteristic, we conducted logarithmic processing to obtain the digitalization level (DIG) index. **Table 1** shows the characteristic words related to the digitalization level.

As can be seen in **Table 1**, a series of high-frequency vocabulary is filtered out through the Python-based Jieba Chinese word segmentation function. These digital technology keywords can be roughly divided into big data technology, Internet, Internet of Things technology, smart technology, cloud, cloud computing technology, information technology, and blockchain technology,

TABLE 1 | Keywords related to the digitalization level.

Big data technology	Big data, digital technology, digital finance, digital terminal, digital intelligence, digital marketing, digital information, digital communication, digital control, digital image, digital network, credit investigation
Internet, Internet of Things technology	Internet of Things, Internet, Industrial Internet, Internet Platform, Internet+, Mobile Internet, Internet Finance, B2B, B2C, O2O, C2B, 5G, 5GtoB, Integrative Network, Internet Application, Industrial Internet, E-commerce, Mobile Payment, NFC Payment
Intelligent technology	Artificial intelligence, intelligence, machine learning, smart robots, smart manufacturing, smart transportation, smart logistics, smart grid, smart warehousing, smart healthcare, smart environmental protection, smart production, business intelligence, mobile intelligence, smart factory, smart management, smart customer service, intelligent network, intelligent terminal, intelligent agriculture, intelligent water conservancy, AI, ERP, MES, deep learning, image recognition, virtual reality, VR, AR, face recognition, autonomous driving, voice recognition
Cloud, cloud computing technology	Cloud platform, cloud service, industrial cloud, cloud ecology, cloud supercomputing, cloud digital intelligence, secure multi-party computation, EB-level storage, cognitive computing, green computing, brain-like computing, cyber-physical systems, stream computing, graph computing
Informatization	Information technology, information sharing, information network, information system, two informatizations (digital industrialization and industry digitization), three informatizations (digital industrialization, industry digitization, and digital governance), four informatizations (digital industrialization, industry digitization, digital governance, and data valuation)
Blockchain technology	Blockchain, distributed computing, digital currency

which is in line with the current understanding of digitization on mainstream literature (Klerkx et al., 2019; Lioutas et al., 2021).

(3) Control variables. According to the existing literature and the actual situation (Quan, 2009; Fuglie, 2018; Zhang et al., 2019), the control variables of this paper consider the two aspects of agricultural production conditions and the socio-economic environment. Agricultural production conditions directly affect the growth and changes of agricultural total factor productivity. Agricultural production conditions generally adapt to the socio-economic environment and can affect agricultural total factor productivity. Specifically, the installed capacity of hydropower stations (Elect), the labor quality (Labqua), and the effective irrigation area (Irrigation) are used to control agricultural production conditions. The social and economic environment is controlled by the share of financial support for agriculture in fiscal expenditure (Finsup) and the level of regional economic development (GDP). At the same time, in order to eliminate the problem of heteroscedasticity, the data are processed logarithmically. The definitions of the input and output variables, dependent variables, independent variables, and control variables of the benchmark model are shown in **Table 2**.

Descriptive Statistical Analysis

Descriptive statistical analysis of the variables included in the agricultural total factor productivity measurement model and the benchmark regression model is performed, and the results are shown in **Table 3**.

Among the descriptive statistical results in **Table 3**, the input and output indexes are statistically described in the form of raw data, but they are logarithmically processed and standardized in the subsequent model calculation process.

The descriptive statistical results show that there is a large difference between the minimum and maximum values and the mean values of various input and output indexes. For example, the minimum value of the total output value of agriculture, forestry, animal husbandry, and fishery (Toutput) among output indexes is about 12.8 billion yuan, the maximum value is about 1.0191 trillion yuan, and the mean value is about 356.5 billion yuan. The minimum value (S) of land input among input indexes is 88.6 thousand hectares, the maximum value is 14910.1 thousand hectares, and the mean value is 5535.025 thousand hectares. This means that there are substantial differences between agricultural output and agricultural input in various regions in China. These differences are mainly due to unbalanced regional economic development and the heterogeneity of the population and industrial structure. For example, compared with other provinces, fewer laborers engage in the primary industry in Shanghai, as there is less arable land, the level of economic development is high, and the tertiary industry is the main industry. Meanwhile, more laborers engage in the primary industry in Guangxi Province, as there is more arable land, and the level of economic development is low. In addition, the maximum values of the independent variable agricultural total factor productivity (TFP) and the core explanatory variable digital technology level (DIG) are 0.978 and 10.448, and the minimum values are 0.274 and 3.714, respectively, indicating that there are substantial differences between the agricultural total factor productivity and digitalization levels in various regions in China. Such differences include differences in regional natural conditions, agricultural production infrastructure, labor quality, and financial input, exerting an impact on agricultural total factor productivity.

ECONOMETRIC TEST OF DIGITALIZATION LEVEL ON AGRICULTURAL TOTAL FACTOR PRODUCTIVITY

The Calculation of Agricultural Total Factor Productivity

Table 4 shows the maximum likelihood estimation results of the stochastic frontier production function model (2). It can be seen that the parameter estimation results of the four main input items of land (S), labor (L), mechanical power (K), and

TABLE 2 | Variable names and definitions.

Variable name		Variable definition
Output index	Total output value of agriculture, forestry, animal husbandry, and fishery (Toutput)	The total production value of agriculture, forestry, animal husbandry, and fishery at the end of the year (100 million yuan), taking the natural logarithm
Input index	Land input (S)	Sown area of crops at the end of the year (thousand hectares), taking the natural logarithm
	Labor input (L)	Number of employees in the primary industry at the end of the year (10,000 people), taking the natural logarithm
	Capital input (K)	The total power of agricultural machinery at the end of the year (10,000 kilowatts), taking the natural logarithm
	Intermediate product input (M)	Consumption of chemical fertilizers at the end of the year (10,000 tons), taking the natural logarithm
Dependent variable	Agricultural total factor productivity (TFP)	The stochastic frontier analysis function and agricultural total factor productivity estimated with the "one-step method"
Independent variable	Digitalization level (DIG)	The digitalization level of each region, taking the logarithm
Control variable	Installed capacity of hydropower stations (Elect)	Installed capacity of hydropower stations at the end of the year (10,000 kilowatts), taking the natural logarithm
	Labor quality (Labqua)	Population that has received education in a rural high school (including technical secondary school) or more/Number of employees in the primary industry
	Effective irrigation area (Irrigation)	Effective irrigation area at the end of the year (thousand hectares), taking the natural logarithm
	Share of financial support for agriculture in fiscal expenditure (Finsup)	Share of financial support for agriculture in fiscal expenditure at the end of the year (100 million yuan)/Total fiscal expenditure (100 million yuan)
	Level of regional economic development (GDP)	Per capita GDP at the end of the year (ten thousand yuan/person)

TABLE 3 | Descriptive statistics of variables.

	Variable	N	Mean	sd	Min	p50	Max
Output index	Toutput	248	3564.637	2483.635	127.997	3277.467	10,190.578
Input index	S	248	5359.025	3885.271	88.600	5476.250	14,910.100
	L	248	874.130	615.047	39.400	765.445	2652.000
	K	248	3340.191	2910.901	94.000	2548.900	13,353.000
	M	248	185.794	146.838	4.400	202.850	716.10
Dependent variable	TFP	248	0.693	0.190	0.274	0.669	0.978
Independent variable	DIG	248	7.168	1.462	3.714	7.220	10.448
Control variable	Finsup	248	0.119	0.036	0.041	0.118	0.244
	Elect	248	4.355	1.867	0.405	4.667	7.153
	Irrigation	248	7.231	1.089	4.694	7.397	8.729
	GDP	248	5.727	2.821	2.283	4.870	16.489
	Labqua	248	0.388	0.382	0.090	0.271	2.587

fertilizer (M) are all significant at the 1% level, and most of the remaining parameters have also passed the *T* test. Among them, the coefficient of γ is 0.986 and passes the *T* test at a significance level of 1%. The γ value is very close to 1, which shows that technical inefficiency is the main component of the joint random disturbance term, accounting for 98.6%, while the influence of the random error term on the inefficiency is only 1.4%, indicating that it is appropriate to use the stochastic frontier production function model in this paper.

Table 4 shows that the input parameters of land, mechanical power, and fertilizer are significantly positive, indicating that, for every 1% increase in the sown area of crops, the agricultural output will increase by 0.5291%. For every 1% increase in agricultural machinery input, agricultural output will increase by 0.1382%. For every 1% increase in fertilizer input, agricultural output will increase by 0.5067%. This result is consistent with the fact that large-scale, mechanized, and scientific agricultural production in China brings high yields and high returns. The labor input coefficient is significantly negative, indicating that the increase in labor input actually reduces agricultural output. The result is the same as the study by Zhang et al. (2019). The negative correlation between labor input and agricultural output is mainly due to the fact that labor income is much higher than agricultural income, which leads to the transfer of rural labor. At the same time, agricultural machinery has a substitution effect on labor (Otsuka et al., 2016). At the moment, China's agriculture

TABLE 4 | Estimated result of stochastic frontier production function.

	Coefficient	Standard-error	t-Ratio
Constant term	0.3908***	0.0511	7.6496
lnS	0.5291***	0.1111	4.7638
lnL	−0.3378***	0.0851	−3.9693
lnK	0.1382***	0.0464	2.9802
lnM	0.5067***	0.1135	4.4642
t	−0.0024	0.0077	−0.3047
lnS*lnL	0.0382	0.2852	0.1341
lnS*lnK	−0.1372	0.4135	−0.3319
lnS*lnM	−2.7771***	0.4443	−6.2500
lnL*lnK	0.0039	0.2650	0.0147
lnL*lnM	0.8673***	0.3355	2.5852
lnK*lnM	0.2540	0.3737	0.6797
t*lnS	−0.0450***	0.0109	−4.1179
t*lnL	0.0543***	0.0068	7.9225
t*lnK	0.0002	0.0064	0.0341
t*lnM	−0.0166*	0.0088	−1.8910
$(\ln S)^2$	1.2337***	0.2914	4.2337
$(\ln L)^2$	−0.3795**	0.1942	−1.9539
$(\ln K)^2$	0.0321	0.1471	0.2184
$(\ln M)^2$	0.6077***	0.1954	3.1096
t^2	0.0108***	0.0016	6.8639
σ^2	0.1793	0.1213	1.4786
γ	0.9860***	0.0097	101.5146
Likelihood	307.0211		
LR		578.2407	
Observations		248	

, **, and * indicate significance at the levels of 10, 5, and 1%, respectively.*

TABLE 5 | Benchmark regression results for full samples and sub samples.

	(1) Full sample	(2) Full sample	(3) Develop = 1	(4) Develop = 0
DIG	0.0123***	0.0098***	−0.0044	0.0142***
	(4.54)	(3.30)	(−0.85)	(3.93)
Finsup		0.1203***	0.4889***	−0.0101
		(2.62)	(8.47)	(−0.29)
Elect		−0.0242**	−0.0387***	−0.0173
		(−2.42)	(−3.29)	(−1.14)
Irrigation		−0.0327*	0.0056	−0.0391
		(−1.76)	(0.28)	(−1.53)
GDP		−0.0073***	−0.0025	−0.0113***
		(−5.02)	(−1.46)	(−5.41)
Labqua		0.0184*	0.0006	−0.0280
		(1.86)	(0.06)	(−1.29)
_cons	0.6051***	0.9854***	0.9014***	0.9349***
	(31.28)	(6.43)	(5.03)	(4.59)
Year	YES	YES	YES	YES
Province	YES	YES	YES	YES
N	248	248	125	122
Adj-R^2	0.9985	0.9989	0.9990	0.9992

**, **, and ***indicate significance at the levels of 10, 5, and 1%, respectively, and the value in parentheses is the t value; there is a single case in the economically developed area (Develop = 1), and it is eliminated in the regression.*

is currently transforming into large-scale and mechanized production. According to the data released by the Ministry of Agriculture and Rural Affairs in the 2020 press conference, the comprehensive mechanization level of the cultivation and harvest of China's main crops has exceeded 70% since the 13th Five-Year Plan. In the limited accommodating space, agricultural machinery replaces a substantial amount of manpower. As such, too much manpower input will cause labor redundancy, which will negatively affect large-scale and mechanized agricultural production. In addition, with the increase in labor costs, excessive labor input will reduce the profit rate of agricultural production. Therefore, labor input and agricultural output are negatively correlated, but this does not negate the benefits brought by high-quality agricultural labor input.

Benchmark Regression Results

In order to verify Hypothesis 1 (H1), Benchmark Model (3) is first used to study the overall impact of digitalization levels on agricultural total factor productivity. Column (1) of **Table 5** is the case where no control variables are added to study the basic relationship between the digitalization levels and the total factor productivity of agriculture. Column (2) is the regression result after adding various core control variables to control the interference of other important factors on the research conclusion.

At the same time, in order to verify Hypothesis 2 (H2), that is, to explore the heterogeneous results produced by differences in regional economic development levels, per capita GDP is used to measure regional economic development levels and constructs a dummy variable for economic development. If the per capita GDP of a region is greater than the annual mean value, then it is an economically developed area, that is, Developed = 1; otherwise, it is an economically underdeveloped area, that is, Developed = 0.

Table 5 shows that, regardless of whether the control variables are considered, regional digitalization can significantly increase agricultural total factor productivity (both are positively correlated at the 1% significance level). Thus, Hypothesis 1 is verified. Specifically, improving the digitalization level can greatly boost the upgrading of agricultural technology, and the use of modern production technology can effectively improve agricultural total factor productivity; on the other hand, regional digital development can further optimize the external conditions of agricultural production including information elements and capital elements, alleviate the adverse effects of asymmetric market supply and demand caused by factors such as distorted resource allocation and information communication failure, thereby improving agricultural total factor productivity. After various control variables are added, the coefficient of the core explanatory variable DIG drops slightly, which shows that the control variables considered in Benchmark Model (3) in this paper are reasonable. Specifically, the Finsup parameter is estimated to be significantly positive at the level of 1%, indicating that financial support for agriculture has achieved good results. For developing countries, backward agricultural production equipment is an important factor restricting agricultural production efficiency. Providing farmers with funds to purchase mechanical and digital equipment helps popularize mechanized and digital production equipment, while financial subsidies can stimulate farmers' enthusiasm for production and alleviate the decline in working-age population in rural areas. To sum up, financial support for agriculture can significantly improve agricultural total factor productivity. In addition, labor quality (Labqua) and agricultural total factor productivity are positively correlated at a significance level of 10%, which indicates that the improvement of labor quality can significantly improve agricultural total factor productivity. The reason may be that agricultural labor forces cannot use agricultural machinery and equipment, digital equipment and other agricultural input factors, or acquire and understand market information without certain knowledge. Labor forces with higher quality can better adapt to digital technology, better use the "digital dividend" and timely access to market information with the help of digital platforms. As the improvement of labor quality can effectively alleviate the "digital divide" problem, labor quality is positively correlated with agricultural total factor productivity. This result is also consistent with the reality.

However, the installed capacity of hydropower stations (Elect) and the effective irrigation area (Irrigation) are significantly negatively correlated with agricultural total factor productivity. This is mainly due to the fact that hydropower is not the main source of electricity in China and is closely related to geographical conditions, and China's power supply situation also varies greatly with regional characteristics. The effective irrigation area is related to the area of arable land. The arable land area in China is unevenly distributed, and the arable land area and the effective irrigation area are significantly smaller in economically developed areas. For example, in economically developed areas such as Beijing and Shanghai, there is less hydropower, electric power is mainly used for the tertiary industry and residents' lives, and the effective irrigation area is relatively small. However, a high labor quality, high mechanical power input, and a high digitalization level can also ensure high agricultural total factor productivity. At the same time, the effective irrigation area is related to the scale of farmland, and previous studies have found that there is an inverse relationship between the scale of farmland and land productivity (Feder, 1985; Barrett, 1996; Barrett et al., 2010). The results of this paper are similar to those of previous studies. On top of that, the level of regional economic development (GDP) and agricultural total factor productivity are also negatively correlated at a significance level of 1%, which reflects the inherent characteristics of economically developed regions; that is, economically developed regions are mainly driven by the tertiary industry, and the more developed the economy, the smaller the proportion of agricultural production. Compared with the primary industry, the tertiary industry can bring higher added value and economic transmission effects. Therefore, the main goal of agricultural production in these regions is to maintain the food supply security line and meet the basic needs of the people in the region. This is in line with China's reality.

Columns (3) and (4) of **Table 5** are the heterogeneous results caused by differences in economic development levels. It can be seen that, under the sub samples of economically developed regions, the estimated coefficient of the digitalization level is negative but not significant, which shows that digitalization has no significant effect on the agricultural total factor productivity of economically developed regions. In the sub samples of economically underdeveloped regions, the regression coefficient of digitalization level is positive at the 1% significance level, indicating that digitalization can significantly improve the agricultural total factor productivity in economically underdeveloped regions. The reason may be that a high labor quality, infrastructure construction, and agricultural subsidies in economically developed regions lead to high agricultural production efficiency benchmarks. Moreover, efficiency growth in economically developed regions may have reached a state of convergence. As a result, a higher digitalization level is needed to significantly improve agricultural total factor productivity (which means a higher threshold effect value). In other words, digital development cannot significantly promote agricultural total factor productivity in a short period of time, which makes it impossible for us to clarify the promotion effect of digital development on agricultural total factor productivity at the moment. In addition, the fact that the focus of economically developed areas is not on the primary industry, the decline in agricultural labor forces and the loss of farmland lead to a skewed allocation of resources, so currently the radiation effect of the digitalization level may act more on secondary or tertiary industries, and the agricultural sector can hardly be promoted by the digitalization. In economically underdeveloped regions, many laborers engage in the primary industry, the labor quality is poor, the infrastructure is underdeveloped (Gorelick and Walmsley, 2020), agricultural subsidies are lacking, and agricultural production is still growing. Therefore, a rising regional digitalization level in economically underdeveloped regions can optimize the entire agricultural value chain, such as production, market information, and factor circulation, making up for the deficiency of insufficient investment in related facilities, and significantly improving the agricultural total factor productivity.

Endogenous Treatment and Robustness Test

Endogenous Treatment

In this paper, there is no reverse causality between the digitalization level at the provincial level and the agricultural total factor productivity, but there may still be errors in the results due to missing variables and measurement errors, resulting in endogenous problems. Compared with the two-stage least squares method (2SLS), the generalized method of moments (GMM) can better deal with the autocorrelation and heteroscedasticity of the data (Lin and Du, 2018). Thus, the instrumental variable-generalized method of moments

(IV-GMM) is adopted to test Benchmark Model (3) and eliminate the possible impact of endogeneity.

Specifically, considering that there may be a certain lag in the effect of digitalization at the regional level on agricultural production, this paper refers to the practice of Chong et al. (2013) of choosing a digitalization level lagging by one stage and the mean value index of digitalization level (DIG_IV) of provinces with similar economic development levels in the same year as the instrumental variable and to test Model (3) with IV-GMM. As far as the relevance of the instrumental variable is concerned, scientific research, infrastructure construction, and practical applications of regional digital technology require financial support, which means that the regional digitalization level is largely affected by the level of economic development. That is to say, regions with similar economic development levels have similar levels of technological development (Li et al., 2020), and the corresponding inputs differ little, so the digital technology levels are also similar. This instrumental variable is relevant. In addition, due to the geographical difference, it is difficult for the digitalization level of each region to affect the agricultural production of other provinces. This is consistent with the exogenous nature of the instrumental variables. **Table 6** reports the IV-GMM regression results.

Column (1) of **Table 6** is the regression results of the first stage. It can be seen that the estimated coefficients of the selected instrumental variables are positively correlated with the digitalization level DIG at the significance levels of 1 and 5%, which proves that the instrumental variables are in line with the correlation condition. In addition, the F statistic of the first stage estimation result is >10, indicating that there is no weak instrumental variable problem. The results of the second stage show that, after dealing with the endogenous problem, the digitalization level and agricultural total factor productivity are positively correlated at a significance level of 1%, and the estimated coefficient has risen from 0.0098 to 0.03. This indicates that some endogeneity factors previously reduced the coefficient of explanatory variables, and the estimated parameters of explanatory variables in this paper are revised after overcoming certain endogeneity factors. At the same time, underidentification and over-identification tests are carried out. The test results show that there is no underidentification or over-identification of instrumental variables, so the selection of instrumental variables is reasonable.

TABLE 6 | IV-GMM test results.

	(1) First stage DIG	(2) Second stage TFP
L.DIG	0.3463*** (4.39)	
DIG_IV	0.1335** (2.20)	
DIG		0.0300*** (3.33)
Finsup	0.3847 (0.45)	0.0838** (1.98)
Elect	0.3194 (1.42)	−0.0312** (−2.65)
Irrigation	0.6804 (1.58)	−0.0655** (−2.17)
GDP	−0.0046 (−0.16)	−0.0057*** (−3.06)
Labqua	−0.6659*** (−3.45)	0.0300* (1.95)
_cons	−2.1824 (−0.70)	1.0271*** (5.30)
Year	YES	YES
Province	YES	YES
F Value	13.57*** [0.0000]	
Kleibergen-Paap rk LM statistic (Underidentification test)		20.08 [0.0000]
Hansen J		0.032 [0.8585]
N	217	217
Centered R^2	0.9989	

**, **, and ***Indicate significance at the levels of 10, 5, and 1%, respectively, and the value in parentheses is the t value; the number in square brackets is the p value of the test result.*

Robustness Test

(1) The PSM-DID method. The core conclusion of this paper is that digitalization has significantly promoted agricultural total factor productivity. In 2016, the National Development and Reform Commission approved the establishment of national big data comprehensive pilot zones in eight regions of 10 provinces or municipalities directly under the Central Government. To further verify the validity of this conclusion, considering that the regional digital development policy is an excellent quasi-natural experiment, the PSM-DID method is used to investigate the impact of regional digital construction on agricultural total factor productivity. The PSM-DID method can effectively correct the selective bias problem through propensity score matching (PSM), alleviate the endogeneity problem through difference in differences (DID), and reduce the omitted variable bias to a certain extent (Wu et al., 2021). This means the conclusions of this paper are robust.

The establishment of national big data comprehensive pilot zones is a reform policy proposed by the State Council to press ahead with regional digital construction and better integrate digital technology with economic production. The impact of changes in regional digital technology levels on agricultural total factor productivity before and after the implementation of the policy can prove the core conjectures of this paper to a certain extent.

The economic level and agricultural production were specifically selected for the following covariates: the per capita GDP, the share of financial support for agriculture in fiscal expenditure, the effective irrigation rate, the total power of agricultural machinery (taking the natural logarithm), and the number of employees in the primary industry (taking the natural logarithm). The entropy matching method does not need to set the specific form of the model and can perform high-order matching without losing samples. In view of the sample size in this study, it is an efficient matching method (Yang and Hou, 2020) and fits this situation well. Thus, the entropy matching method is used for matching. The entropy matching results are shown in **Table 7**.

Table 7 shows that the *p* value of each covariate before matching is <0.01, which indicates that there is a significant difference between the experimental group and the control group. After entropy matching, the absolute value of the standard deviation of each covariate is 0%, there is no significant difference, and the deviation is reduced by 100%. This shows that the variables selected in this study are appropriate. It also shows that PSM regression has made the experimental group and the control group roughly similar, and the model is robust. In addition, the dummy variable yeardummy was set before the implementation of the policy and was cross-multiplied with the experimental group or the control group (Treat × yeardummy) after it was incorporated into Model (4) for the equilibrium tendency test. The test results are shown in **Table A1** of **Appendix A**. The test results show that the coefficient of the cross-product term (Treat × yeardummy) are not significant, indicating that the experimental group and the control group meet the equilibrium tendency before the implementation of the policy.

The regions approved for the construction of national big data comprehensive pilot zones in 2016 are Guizhou, Beijing, Tianjin, Hebei, Guangdong, Shanghai, Henan, Chongqing, Liaoning, and Inner Mongolia. These regions are included in the experimental group, and the remaining regions are in the control group. The difference-in-differences model is adopted on the experimental group and the control group before and after the implementation of the digital development policy to effectively eliminate the internal differences between individuals and the bias caused by the time trend unrelated to the experimental group and obtain the "net effect" of the digital development policy on agricultural total factor productivity. The measurement model constructed is

$$TFP = \alpha_0 + \alpha_1 Treat \times Post + \alpha_2 Control_{it} + \theta_i + \tau_t + \varepsilon_{it} \quad (4)$$

In model (4), when a sample is in the experimental group, *Treat* is 1, and when a sample is in the control group, *Treat* is 0. When the year is ≥2016, *Post* is 1; otherwise, it is 0. The coefficient of cross-product term α_1 of *Treat* and *Post* reflects the change in agricultural total factor productivity before and after the implementation of the digital development policy in a region and is a key parameter to be evaluated in the model. $Control_{it}$ represents other control variables, and the specific meaning remains unchanged. θ_i is an individual fixed effect of the model. τ_t is the time fixed effect, and ε_{it} is the random error term of the model. The regression results are shown in Column (1) of **Table 8**.

(2) The time lag effect. Taking into account that digital technology may have a certain time lag effect on agricultural production, the core explanatory variables and explained variables are further treated with a one-period lag and a one-period lead, respectively. The test results are shown in Columns (2) and (3) of **Table 8**.

(3) GMM dynamic panel analysis. The agricultural total factor productivity has a certain degree of sustainability, that is, serial correlation. To solve this problem, dynamic panel data are further constructed, the lag term of the explained variable is used to control the influence of initial conditions on the agricultural total factor productivity, and the first-order difference generalized method of moments (FD-GMM) is adopted to perform regression. The regression results are shown in Column (4) of **Table 8**.

Column (1) of **Table 8** is the regression result of PSM-DID. It can be found that the regression coefficient of treat × post is significantly positive at the level of 5%, which indicates that, after the implementation of the digital development strategy, the regional digitalization level was promoted, and the agricultural total factor productivity significantly increased. Columns (2) and (3) are the test results after considering the time lag effect. It can be seen that the digitalization level and agricultural total factor productivity are still positively correlated at a significance level of 1%. This shows that the promotion effect of the digitalization on agricultural total factor productivity has not decayed over time, but this reflects that the development of digital technology in various regions can exert a duplicate effect on agricultural total factor productivity in a longer time series. This further proves the correctness of the core viewpoints of this paper.

Column (4) is the regression result of the GMM dynamic panel. The *p* value of AR(1) test is close to 0, and the *p* value of AR(2) test is 0.648, which means that the model has a first-order serial correlation but no second-order serial correlation. This satisfies the moment condition of GMM estimation. At the same time, *p* values in Sangan's test and the Hansen J test are >0.1, which shows that the model is effective. The regression coefficient of the digitalization level (DIG) is still significantly positive at the 1% level, indicating that, after considering the characteristics of agricultural total factor productivity serial correlation (controlling the explanatory variable lagging one period and the resulting endogenity), regional digitalization can significantly promote agricultural total factor productivity.

The Influence Mechanism of the Digitalization Level on Agricultural Total Factor Productivity

In order to verify Hypothesis 3a (H3a), that is the adjustment mechanism of factor allocation distortion, this paper refers to the research of Hsieh and Klenow (2009), Zhu et al. (2011), and Gai et al. (2015). In this paper, factor distortion is defined as the comparison between factor return and actual return. If the factor distortion index is <1, the factor return is less than the actual price, and the factor price is positively distorted. Otherwise, it is negatively distorted. First, under the CD production function equation, that is, $Y = AS^{\alpha}L^{\beta}K^{\gamma}M^{\delta}$, where Y represents total output, S, L, K, and M represent land, labor, capital, and intermediate product inputs, respectively, and α, β, γ, and δ represent the output elasticity of each input, respectively, A is the total factor productivity, which also indicates technological progress. Since the input of the intermediate products can be adjusted freely and does not face flow limitations (Wang and

TABLE 7 | Entropy matching quality result.

Variable	Unmatched matched	Mean		%Bias	%Reduct |Bias|	*t*-Test	
		Treated	Control			*t*	*p* > |t|
Finsup	U	0.0957	0.1295	−98.1	100.0	−7.65	0.000
	M	0.0957	0.0957	−0.0		−0.00	1.000
Irrigation	U	6.9126	7.3822	−41.9	100.0	−3.23	0.001
	M	6.9126	6.9126	−0.0		−0.00	1.000
GDP	U	7.1160	5.0660	69.9	100.0	5.68	0.000
	M	7.1160	7.1160	0.0		0.00	1.000
lnK	U	7.2986	7.8049	−41.3	100.0	−3.35	0.001
	M	7.2986	7.2986	−0.0		−0.00	1.000
lnL	U	6.1121	6.4698	−29.4	100.0	−2.38	0.018
	M	6.1121	6.1121	−0.0		−0.00	1.000

TABLE 8 | Robustness test.

	(1) PSM-DID	(2) F.TFP	(3) TFP	(4) FD-GMM
Treat × Post	0.0119** (2.49)			
DIG		0.0090*** (3.10)		0.0013*** (3.17)
L.DIG			0.0110 *** (3.86)	
L.TFP				0.9947*** (203.38)
Finsup	0.2137*** (3.01)	0.1188** (2.57)	0.1077** (2.56)	0.0007 (0.39)
Elect	−0.0379*** (−3.07)	−0.0178* (−1.92)	−0.0215** (−2.13)	0.0007** (2.22)
Irrigation	0.0078 (0.38)	−0.0203 (−1.29)	−0.0426* (−1.84)	−0.0006 (−0.47)
GDP	−0.0025 (−1.37)	−0.0081*** (−6.16)	−0.0062*** (−3.82)	0.0001 (1.37)
Labqua	0.0058 (0.57)	0.0262*** (2.89)	0.0106 (0.92)	0.0009** (2.72)
_cons	0.8895*** (4.76)	0.8792*** (6.82)	1.0423 (5.60)	
Year/Province	YES	YES	YES	YES
N	248	217	217	186
Adj-R^2	0.9995	0.9992	0.9991	
AR(1) *p* value				0.037
AR(2) *p* value				0.648
Hansen J *p*-value				0.656
Sargan *p* value				0.659

, **, and * indicate significance at the levels of 10, 5, and 1%, respectively, and the value in brackets is the t value; differential GMM deletes the constant term and does not report R-squared, which does not affect the regression results of the model.*

Li, 2021), it is assumed that there is no distortion in the input of intermediate products. At the same time, based on the actual situation of agricultural production, it is generally believed that land use is free (Zhu et al., 2011). Therefore, this paper only considers the distortions of the capital and labor markets. The marginal outputs of capital and labor are expressed as follows:

$$MRPK = A\gamma S^{\alpha} L^{\beta} K^{\gamma-1} M^{\delta} = \frac{\gamma Y}{K} \tag{5}$$

$$MRPL = A\beta S^{\alpha} L^{\beta-1} K^{\gamma} M^{\delta} = \frac{\beta Y}{L} \tag{6}$$

Assuming that the capital price is the benchmark loan interest rate R and the labor price is the average wage W, the degree of distortion in the capital and labor markets and the overall degree of distortion in the market are, respectively,

$$DisK = \frac{MRPK}{R} \tag{7}$$

$$DisL = \frac{MRPL}{W} \tag{8}$$

$$DisT = DisK^{\frac{\gamma}{\gamma+\beta}} DisL^{\frac{\beta}{\gamma+\beta}} \tag{9}$$

This paper establishes a panel data model to estimate the element elasticity of each region:

$$lnY_{it} = \alpha lnS_{it} + \beta lnL_{it} + \gamma lnK_{it} + \delta lnM_{it} + \theta_t + \rho_i + \varepsilon_{it} \tag{10}$$

Here, Y is the total output value of the primary industry, S, L, K, and M are again, respectively, land, labor, capital, and intermediate product inputs, θ_t represents the fixed effect of controlling time, ρ_i represents the individual effect of controlling province, and ε_{it} is the random error term of the model. After estimating the elasticity of factors in each region from Model (10), the overall distortion of the market can be estimated by model (7)–(9). After the overall market distortion degree (DisT) is obtained, the cross-product term (DIG×DisT) between it and the explanatory variable DIG is added to Benchmark Model (3). The coefficient of the cross-product term is the adjustment effect of the distortion of market factor allocation. The test results are shown in **Table 9**.

TABLE 9 | The influence mechanism of the digitalization level on agricultural total factor productivity.

	(1) TFP	(2) TFP
DIG	0.1212*** (4.16)	0.0074** (2.37)
DIG × DisT	−2.7068** (−2.19)	
DIG × Scale		0.0011** (2.17)
Finsup	0.1022** (2.11)	0.1269*** (3.00)
Elect	−0.0310*** (−2.81)	−0.0242** (−2.49)
Irrigation	−0.0347* (−1.89)	−0.0438** (−2.36)
GDP	−0.0066*** (−4.37)	−0.0065*** (−4.38)
Labqua	0.0128 (1.25)	0.0147 (1.50)
_cons	1.0265*** (6.72)	1.0647*** (6.96)
N	248	248
Adj-R^2	0.9989	0.9989

**, **, and ***Indicate significance at the levels of 10, 5, and 1%, respectively, and the value in brackets is the t value.*

In addition, in order to verify Hypothesis 3b (H3b), that is, the adjustment mechanism of scale, this paper defines large-scale production (Scale) as the ratio of the sown area of crops to the number of laborers, that is, the average sown area of labor (taking the logarithm to ease measurement errors and heteroscedasticity issues), and adds its cross-product term with the digital technology level (DIG) to Benchmark Model (3). The coefficient of the cross-product term DIG × Scale is the adjustment effect of large-scale production. The test results are shown in **Table 9**.

Column (1) of **Table 9** is the regression result of the adjustment effect of the distortion of market factor allocation. The coefficient of the interaction term between the digitalization level and the distortion of market factor allocation (DIG × DisT) is significantly negative at the 5% level, indicating that, when the market factor allocation is distorted, or the market factor allocation is not efficient, the promotion effect of digitalization on agricultural total factor productivity will be significantly weakened. On the other hand, when the efficiency of market factor allocation is improved, that is, after the distortion of market factor allocation is improved, the promotion effect of digitalization on agricultural total factor productivity will be significantly strengthened. Hypothesis 2 is thus verified. The mechanism of action may be as follows: Resources tend to be input in urban enterprises rather than the agricultural sector due to market distortions (Au and Henderson, 2006), which aggravates the negative consequences brought by the decline in agricultural labor forces and the loss of farmland, seriously hindering the improvement of agricultural production efficiency. Alleviating market distortions will effectively improve resource input bias and guide resources to enter the agricultural sector, thereby enhancing the role of digitalization in promoting agricultural total factor productivity. Specifically, alleviating price distortions in the agricultural market can help correct the profits of the agricultural sector, stimulate the enthusiasm of producers, and effectively enhance the promotion effect of digital technology on agricultural total factor productivity; alleviating the distortion of capital allocation can reduce the ineffective allocation of capital, increase the capital inflow to the agricultural sector, provide financial support for agricultural digital equipment and offer labor forces with the opportunity to learn digital technology, thereby enhancing the promotion effect of digital technology on agricultural total factor productivity. At the same time, after the distortion of the allocation of labor factors in the market is alleviated, wages of the agricultural sector will be raised to introduce high-quality talents (Li and Ma, 2021), thereby improving the adaptability of agricultural labors to digital technology, easing the "digital divide" problem in the agricultural sector, and further enhancing the role of regional digitalization in promoting agricultural total factor productivity. In addition, the reduction in the degree of market distortion indicates an improvement in resource allocation efficiency, whether it is a capital element or a labor element. Improving the allocation efficiency can further enhance the role of digital technology in promoting agricultural total factor productivity and optimizing the agricultural production value chain.

Column (2) of **Table 9** is the regression result of the adjustment effect of large-scale production. The coefficient of the cross-product term DIG × Scale is significantly positive at the 5% level, indicating that large-scale production has significantly enhanced the role of digitalization in promoting agricultural total factor productivity. That is, the larger the scale of farmland production, the greater the promotion effect of digitalization on agricultural total factor productivity. Hypothesis 3 is thus verified. The reasons for this may be as follows: First, in terms of technology input cost, large-scale production is conducive to reducing the unit input cost of digital technology. Cost reduction contributes to the application of digital production technology in the agricultural sector both in depth and in breadth, and wider application and more advanced digital technology means a greater improvement in agricultural total factor productivity. Second, at the level of technological adaptation, the application of agricultural digital technology is more suitable for large-scale production of land. Agriculture land fragmentation limits the application of digital technology, and satellite imagery, smart water conservancy and other technologies are more suitable for large-scale production, so large-scale farmland and digital technology have better synergistic effects. Third, large-scale production is conducive to the acquisition of digital information for agricultural production, and these digital information will become agricultural digital information assets, providing a reference for subsequent agricultural production-related decisions. Based on the above reasons, large-scale agricultural production can positively enhance the promotion effect of regional digitalization on agricultural total factor productivity. Previous studies have found that there may be an inverse relation between farm scale and production efficiency, and the results of this study may also indicate that digital technology is an important support condition for large-scale production, that is, the expansion of farmland production on the basis of improving regional digitalization level can significantly promote the growth of agricultural total factor productivity. Digital technology and agricultural machinery have the same labor substitution effect, ensuring better results for large-scale production. This conclusion provides empirical evidence for the policy guidance of large-scale production.

CONCLUSIONS AND RECOMMENDATIONS

As populations grow, slowdowns in agricultural productivity growth and the extensive development of agriculture lead to unsustainable development in some parts of the world. Under the circumstance, food security is challenged, and agricultural transformation is imminent. This paper uses data from 30 provinces or municipalities in Mainland China from 2013 to 2020, identifies keywords related to digitization, adopts the number of Internet searches using "prefecture-level cities or municipalities + keywords related to digital technology" to measure regional digitalization levels, discusses the impact of regional digitalization levels on agricultural total factor productivity and the heterogeneity of economic development level, and further analyzes the adjustment mechanism of market factor distortion and large-scale production. The following conclusions can be drawn:

First, regional digitalization can significantly increase agricultural total factor productivity. Digital technology can make agricultural production, the supply of consumables, the transportation and sales of finished products, and other value chains more efficient (Wolfert et al., 2017; Creydt and Fischer, 2019). Regional digital construction can alleviate the shortage of agricultural digital technology input and the "digital divide" of laborers, which are important reasons behind inefficient agricultural production (Benyam et al., 2021).

Second, the impact of regional digitalization levels on agricultural total factor productivity is heterogeneous. Regional digitalization can significantly raise agricultural total factor productivity in economically underdeveloped regions but not in economically developed regions. However, the fact that digitalization does not have a significant effect on agricultural total factor productivity in economically developed regions does not mean that these regions should pay less attention to digital construction. On the contrary, since digital technology is still not widely applied in agricultural production and external markets, these regions should continue to develop digital technology in order to break the threshold for the actual utility of digital technology. This study points out that an important means of improving agricultural total factor productivity in economically underdeveloped regions or developing countries is the promotion of regional digitalization. It is also an important route to green and sustainable agricultural growth.

Third, the distortion of market factors and large-scale production have a significant regulatory effect. The lower the degree of market factor distortion, the greater the effect of digitalization in promoting agricultural total factor productivity; the larger the scale of farmland production, the greater the role of digitalization in promoting agricultural total factor productivity. The inefficient allocation of market elements indicates high information asymmetry between the supply and demand parties. Invalid allocation further causes a waste of resources, hinders market development, and affects agricultural production. Alleviating the distortion of market factor rationing will help digital technology to better promote the connection between supply and demand in the agricultural market and will further strengthen the role of digitalization in promoting agricultural total factor productivity. At the same time, this is an important foundation for creating a low-risk, high-return market. Some studies have found that farm scale and production efficiency are often inversely related (Feder, 1985; Barrett, 1996). However, with the development of agricultural production technology, the adaptation scenarios of these studies have changed greatly. For example, Otsuka et al. (2016) found that, as machinery replaces a large number of labors in Asia, farm scale and production efficiency have shown a positive correlation. This research reflects that the application of agricultural machinery technology has changed the current agricultural production scene. This paper is based on China's digital construction, which may mean that digital construction is also an important support condition for large-scale agricultural production in developing countries. Developing countries can popularize agricultural machinery while improving the level of regional digitalization, and bottlenecks in digital technology investment costs proposed by Benyam et al. (2021) can also be alleviated in large-scale production. This will have a more significant promotion effect on agricultural total factor productivity. In short, our empirical evidence shows that large-scale production and digital technology complement each other.

Based on the above conclusions, the following recommendations are put forward: First, governments should work hard to promote digitalization as a way to increase agricultural total factor productivity. Digital construction in economically developed regions is the subsequent growth driver for agricultural production, while digital construction is an opportunity for economically underdeveloped regions to turn to green and sustainable development. At the same time, it is necessary to work hard to solve the "digital divide" of laborers and the problem of digital technology adaptation, to strengthen the practical application of digital technology, to achieve industry–university–research cooperation, and to popularize digital technology education in order to improve the labor quality and promote the transformation of the workforce. Second, government regulatory agencies should establish an information exchange platform for the supply and demand parties of the agricultural market through digital technology to optimize the external environment of the market and the efficiency of factor allocation and to reduce the waste of resources caused by ineffective allocation. In addition, it is necessary to improve government transparency and citizen participation and to obtain effective feedback on policy effects, thereby solving the problem of market distortion caused by ineffective policies.

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 authors.

AUTHOR CONTRIBUTIONS

WF and RZ: conceptualization, writing—original draft preparation, and writing—review and editing. WF: data curation and formal analysis. Both authors have read and agreed to the published version of the manuscript.

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Sustainable Food Systems and Farmers' Welfare Status Distribution in Oyo State, Nigeria: Building Buffers Against Shocks and Stressors Through Resilience Pillars

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This study investigated the effect of resilience components and indicators on households' welfare distribution in the study area, using the data collected from households' surveys. Respondents were drawn from the study area through the multistage random sampling technique; while the data obtained from 363 sampled respondents were analyzed and described through the use of descriptive statistics (frequency distribution, percentages, and cross tabulation technique). The resilience tool of the Food and Agriculture Organization of the United Nations (UN-FAO) was adopted to measure the resilience pillars through their corresponding components/indicators. Similarly, a quantile regression econometric model was used to estimate the effect of the resilience pillars vis-à-vis the indicators on welfare distribution in the study area. The results indicated that the majority of the respondents fall within the low quintiles of households' welfare, while women were found to be disproportionately vulnerable to shocks, as many of them fall within the low welfare class. The resilience pillars/components were found to have varying degrees of significance and direction of movement with quintiles of households' welfare status. This was observed across all the quintiles (0.1, 0.25, 0.50, 0.75, and 0.90; that is, 10, 25, 50, 75, and 90th quintiles), respectively. The study recommended proper and transparent implementation of functional social protection programs to reduce households' vulnerability to shock and stressors. There is also the need for investments to be made across all pillars and indicators of resilience to build sustained households' resilience capacity and welfare status.

Keywords: shocks, resilience, welfare, quantile regression, Oyo State, Nigeria

INTRODUCTION

The concept of resilience has attracted attention from many experts to address the challenges facing all sectors of the economy, including the agri-food system. Food and Agriculture Organization (FAO) and other notable development experts have also been advocating for building resilient systems (both agri-food and non-agri-food) from many perspectives

(Food Agriculture Organization (FAO), 2013; Choptiany et al., 2014). In fact, the International Food and Policy Research Institute (IFPRI) had once organized a conference with the theme "*building resilience for food and nutrition security*" (Fan et al., 2014). All these moves evidently mirror the importance of developing adaptive capacity for resilience building against stresses, shocks and emergencies facing our society, especially the agri-food system. Importantly, resilience study and analysis evaluate the individual or household capacity to manage the effect of shocks from a multi-faceted approach (d'Errico and Di Giuseppe, 2018).

Food Agriculture Organization (FAO) (2019) also noted that the conceptualization of farmers' or farming households' food security status vis-à-vis food insecurity status and other welfare outcomes must incorporate a measure of resilience to a shortfall in well-being status owing to various exigencies such as insufficient and/or lack of productive resources, risks and shocks constituents, including droughts, wars, and economic instability. This also includes unprecedented emergencies such as the current COVID-19 health pandemic and other risks and challenges. Meanwhile, it is important to emphasize that inadequate or lack of access to productive resources (required to build adaptive capacity and overall resilience against shocks) by the less developed countries that are resource-poor poses a big problem to step up to the challenges facing the world, which by extension also has consequential impact and shock on the food systems (Issahaku and Abdulai, 2019; Jones et al., 2022). Further, the global situation on the COVID-19 pandemic is a great shock suffered by the entire sector of the Nigerian economy, including the food sector and sub-sectors; this evidently threatens sustained food availability, accessibility, and affordability due to its significant impact on welfare and other aspects of human development.

Apparently, from the foregoing, building farmers' resilience and adaptive capacity against shocks in an unprecedented health-related pandemic period through access to the required and sufficient productive resources, social investment, and social protection programs are necessary. These are potential game changers for the people, including the smallholder farmers to improve productivity, food availability, farmers' income, and general households' welfare across all the sectors in Nigeria. Therefore, this research interrogated the effect of resilience indicators and components on households' welfare distribution in Oyo State, Nigeria.

THEORETICAL SIGNIFICANCE OF HOUSEHOLDS' WELFARE

Following the study by Barrett and Constas (2014), this study adopted a theory of resilience as it applies to the challenges of international development. This theory presents a sound theoretical argument to promote a more focused measure of resilience for international development applications; and, resilience development is the ability of individuals or households to avoid myriads of shocks and stressors that can propel transition into poverty traps over time.

This conceptualization of the theory of resilience development emphasizes the non-linear and uncertain time path of standards of living, and people's welfare conditions, which could express themselves as vulnerable or non-vulnerable, poor or non-poor, food secure or food insecure, as well as other forms of welfare representations. This theory also underscores the adverse effects of various forms of risk, shocks, or stressors that can be appalling, and capable of transforming people's conditions from good to bad, and bad to worse. Suffice it to say that the theory of developing resilience is concerned about the "stochastic dynamics of human well-being and/or stochastic poverty trap" because it is inversely related to the probability of being vulnerable and remaining vulnerable (Barrett and Carter, 2013; Barrett and Constas, 2014). It is important to emphasize that multiple stable states are not necessary for the existence of poverty traps in the theory of development resilience (Barrett and Carter, 2013).

In line with Barrett and Constas (2014), the variable of interest emphasized in the theory of developing resilience is an individual's or households' of many people's well-being, which can be denoted by "W", and a person or household's unfavorable or chronic state mirrors the sustained deprivation of capabilities, as also explained by the concept of Amartya Sen's "capabilities" (Sen, 1999). Therefore, the capabilities framework is a nested special case defined by welfare and/or well-being indicators such as "income, expenditures, assets, health, food and nutritional status, subjective life satisfaction or security" and, it could also be conceptualized from a multidimensional perspective of welfare measures (Alkire and Foster, 2011).

Given that well-being may increasingly be stochastic, which can also be influenced by myriads of both endogenous and exogenous events, simply put as a disturbance term, e_t so that the progression of well-being over time, from W_t in period t to W_{t+s} in period $t+s$, is dependent on random stressors and/or shocks. In line with Barrett and Constas (2014), an appropriate representation of stochastic welfare dynamics is through conditional welfare expressed by the moment function, m^k $(W_{t+s}|W_t\ ,\ e_t)$, where: m_k represents the kth moment; that is, the mean ($k = 1$), variance ($k = 2$), or skewness ($k = 3$). Now, based on the theory of resilience development, these moments perfectly describe the conditional dynamics of the full distribution of possible welfare outcomes that may be functionally related to resilience capacity.

MATERIALS AND METHODS

The Study Area

The study area is Oyo State (**Figure 1**), which is an inland area located in the southern part of Nigeria, and bounded by many states from the south, north, west, and eastern parts. The climate is equatorial characterized by "wet and dry seasons." The people in the state are predominantly farmers, while most women engage in on-farm and off-farm livelihood activities such as food processing, trading, and artisanship. The relatively high humidity in the area favors the cultivation of arable and tree crops such as like maize, yam, cassava, millet, rice, plantains, cocoa, palm produce, cashew, etc. The State has 33 Local Government Areas (LGAs); of which 28 LGAs are considered rural and semi-rural.

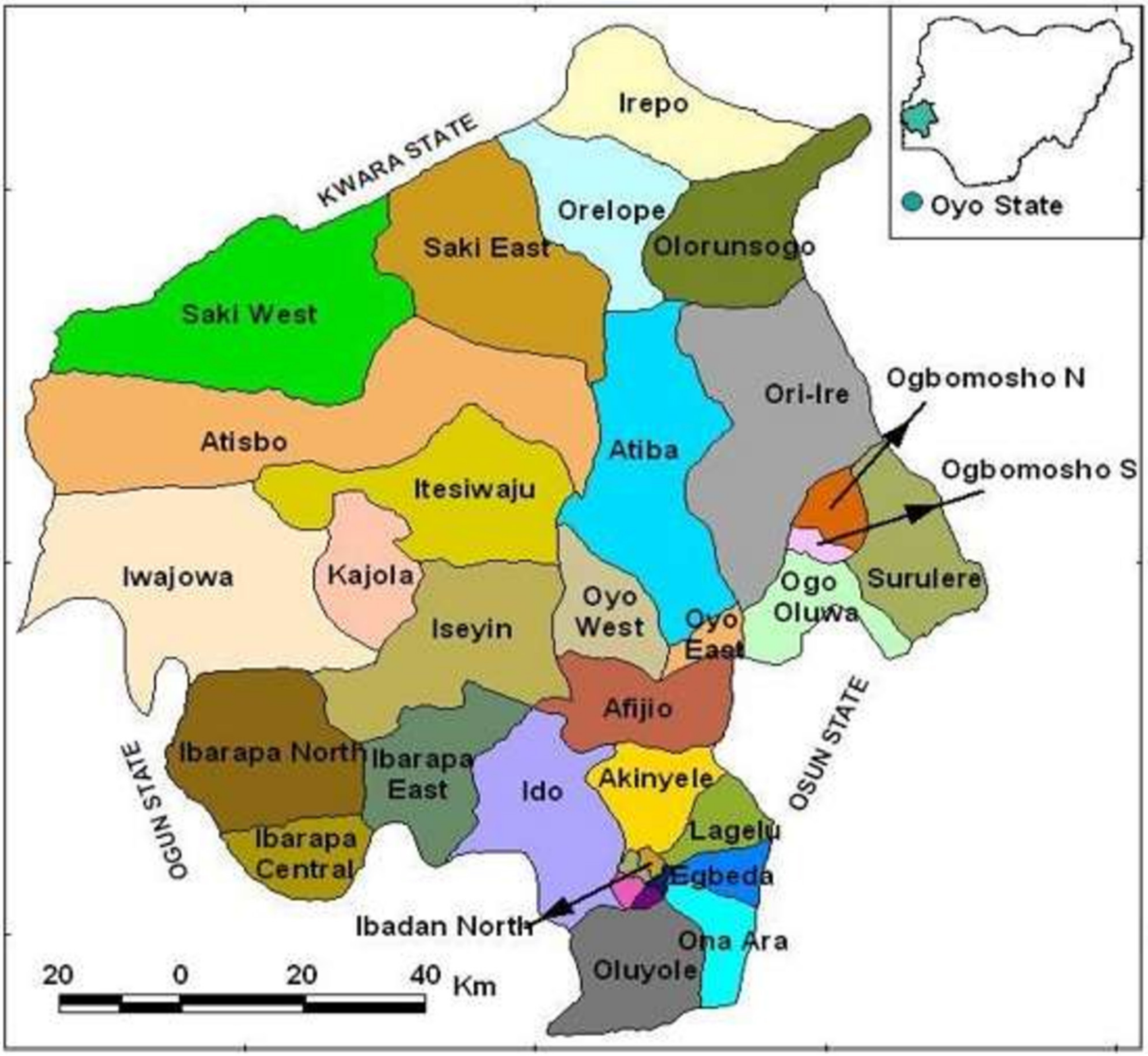

FIGURE 1 | Map of Oyo State, Nigeria.

The State is divided into 4 Agricultural Development Program (ADP) Zones (Ibadan, Ibarapa, Ogbomoso, and Oyo) in the State (www.oyostate.com).

Sampling Technique and Data Collection

A multistage sampling technique was used to select the sample size for this study. Oyo State is made up of 4 Agricultural Development Program (ADP) zones which are structured into different blocks namely: Ibadan/Ibarapa zone with nine blocks, Ogbomoso zone with five blocks, Oyo zone with five blocks, and Saki zone with nine blocks. So, in the first stage, one-third of the blocks in each zone were selected resulting in 10 blocks in total. Because of the homogeneous nature of the villages in the study area, three villages were randomly selected from each of the blocks in the second stage, making 30 selected villages. In the third stage, the study applied a random proportionate to size sampling technique in the selection of the sample size (384 respondents) for this research; this technique was deemed appropriate because of the variations that exist in the population of people across the selected villages.

According to Miaoulis and Michener (1976), the three main criteria which are usually considered in the determination of a suitable sample size for any study are the level of precision, confidence level, and the degree of variability. Therefore, this research selected the representative sample for this study through the validated method for sample size determination for an unknown population, using the confidence level technique of Z-score (Shete et al., 2020). This is expressed as follows:

$$n_0 = \frac{z^2 \times p(q)}{e^2} \qquad (1)$$

The followings are also defined as:

n_0 = Sample size to be estimated

z^2 = Selected critical value of desired level of confidence or risk

p = Estimated proportion of an attribute that is present in the population or maximum variability of the population

$q = 1 - p$

e = error margin

At a 0.05 error margin (95% confidence interval), the sample size is calculated as:

$$n_0 = \frac{(1.96)^2 \times 0.5\,(1 - 0.5)}{(0.05)^2} = 384.16$$

It is important to stress that data from 363 respondents were used in the final analyses, owing to incomplete responses observed from few data collection instruments.

Data Analytical Techniques

The study used descriptive statistics such as frequency distribution, percentages, and cross-tabulation techniques to describe the respondents' personal and demographic attributes, as well as to profile the distribution of respondents based on the welfare quintiles they fall into. Borrowing from Atkinson (1989) as well as Baiyegunhi and Fraser (2011), realized welfare, as against potential welfare was constructed through *per capita* consumption-expenditure approach to measure the welfare indicator used in this study. This was considered an measure as noted by Baiyegunhi and Fraser (2011) citing Atkinson (1989) is driven by the fact that welfare opportunity is a function of income, or suffice it to say that income is assumed to measure potential welfare. On the other hand, consumption-expenditure suggests a "realized welfare or a measure of welfare achievement" (Atkinson, 1989) as cited in Baiyegunhi and Fraser (2011). However, this study is interested in farmers' present achieved welfare (realized welfare) as against future expected welfare gains (potential welfare); apparently, the consumption-expenditure welfare expression concept is an appropriate indicator. Baiyegunhi and Fraser (2011) further buttressed that, poor individuals are assumed to have a relatively constant expenditure pattern on some basic bundles of goods, all things being equal, compared to the income-stream which in most cases is assumed to be erratic and unpredictable.

Therefore, the welfare indicator and expression were constructed by using *per capita* values of consumption-expenditure on food and non-food items. The use of this welfare expression is deemed appropriate for this kind of study because the variable is in continuous form, compared to other similar approaches for constructing welfare indicators (for instance, poverty status and food security status). This approach used *per capita* expenditure approach to construct the poverty or food security line, and it is further rescaled to binary forms, through the use Foster et al. (1984) technique. The technique apparently is not suitable for distributional impact research (Olagunju et al., 2019). Therefore, this study constructed the welfare indicator using the following:

$$W_i = \frac{\textit{Per capita total consumption} - \textit{expenditure for ith household}}{\frac{2}{3}\ \textit{mean per capita total expenditure of all households}} \quad (2)$$

where:

W_i = index of households' welfare status.

appropriate indicator of welfare expression owing to the fact that it is an absolute welfare measure. In the same vein, FAO's RIMA-II model (resilience tool) (Food Agriculture Organization (FAO), 2016) was used to elicit resilience information from the respondents and applied to measure different dimensions and components/indicators of resilience (physical and capacity dimensions, as well as information on natural environment addressing both exogenous and endogenous factors). More so, the quantile regression model was employed as an inferential statistical technique to estimate the influence of resilience components and indicators on households' welfare distribution in the study area.

Modeling Households' Welfare

The household economic behavior under constrained utility maximization was applied to model the level of households' expenditure based on the money-metric indicator of welfare. Households' consumption expenditure is assumed to describe the social and economic environments in which production decisions are made. The preference for the consumption expenditure approach over the income-based household's welfare

FAO's RIMA-II Empirical Model: Introduction and Specification

According to Boukary et al. (2016), the application of the concept of resilience has been proposed by scholars and development experts across many international development corporations for the conceptualization of food insecurity issues (for instance, Alinovi et al., 2010a,b; Food Agriculture Organization (FAO), 2016). The usefulness of the resilience methodological approach as a solid basis for the analysis of individuals' and households' vulnerability to food insecurity cannot be over emphasized (Alinovi et al., 2010a). Resilience, according to Food Agriculture Organization (FAO) (2016) is an important framework applied to gain proper knowledge of the strategies (both short and long terms) needed to build and strengthen the adaptive capacity of individuals and households against shocks and stresses induced by hunger and poverty. Based on theoretical understanding and statistical evidence of relationships, this survey captured the indicators and components of resilience fundamental pillars, as highlighted in Food Agriculture Organization (FAO) (2016). A notable and appealing feature of the resilience framework is that it identifies and describes how shocks and stressors, economic forces, and social conditions of the system, as well as its combined effect, have raised the incidence and severity of vulnerability of a given population [Food Agriculture Organization (FAO), 2016]. Explicitly, the fundamental pillars of resilience and corresponding indicators, according to Food Agriculture Organization (FAO) (2016) and Boukary et al. (2016) are explained as follows:

a. Asset (AST): Possession of capital assets is noted to be useful as a coping mechanism to mitigate shocks induced emergencies. In this study, assets could be held as landed properties, crop and livestock units, jewelry, television, car, bike, dwelling, telephone, etc. Suffice to say that, possession of any of these assets by an individual equals 1 and 0 otherwise.
b. Adaptive capacity (ACS): Adaptive capacity as an indicator mirrors an individual's ability or capability to cope and adapt to shocks in a way that will not disrupt the proper functioning of that individual. For instance, wealth, technology, economies of large scale, access to information and training/skills, access to infrastructure, and institutions are parts of many dynamics that influence an individual's adaptive capacity.

The following variables are appropriate components of this indicator:

Perception: This has to do with the opinion of one's capability to withstand shocks.

Income source: This has to do with livelihood diversification through the count of the individual's source of income. All else equal, it is assumed that individuals with highly diversified sources of income can potentially adapt to any episode of shocks and emergencies.

Migration: This component addresses if an individual has cause to deal with shocks or food scarcity through migration to another location. It is usually captured as a dummy variable.

Credit: This mirrors individual's access to formal and informal credit facilities over the observation period, as well as the nature- of such credit, be it kind or cash; measured as a dummy variable.

c. Social safety nets (SSN): This component interrogates individual's access to social investment and social protection programs, as these are regarded as important means of mitigating crises and emergencies. In the crisis and emergency situations, farmers often resort to getting help and assistance from friends, colleagues, relatives, government and non-governmental organizations, as well as development corporations and charity organizations. Hence, assistance received by individuals as per access to free food distribution, food sale at a moderate price, cash transfers, grain bank, and donations from friends, colleagues, and relatives are good and promising proxies. Thus, reported access to any of these components equals 1 and 0 otherwise.
d. Climate change (CC): In agrarian settings, climate-induced extreme events can highly affect the capacity of the individual to make a living. The conceptualization of climate change in the context of the Intergovernmental Panel on Climate Change implies any alteration or variation in the climatic components over a period of time; such variation could be a result of natural erraticism or human activities. Examples of promising components are evidence of soil-water erosion and soil degradation. Based on this, any reported event equals 1 and 0 otherwise.
e. Access to basic services and quality of the access (ABSQ): Access to basic services can be conceptualized from two perspectives: access to basic services and the quality of access and services. In terms of access, the following are considered good components: access to school, hospital, and other health services, markets, stores, paved roads, safe houses, and water as well as waste disposal systems, etc. Conversely, a good proxy for the quality of access can be the monetary cost of access to services; alternatively, subjective indicators can also be applied, which could capture general opinion about the quality of services and disposition to the security situation in the community or village where the individual is domiciled (Boukary et al., 2016; Food Agriculture Organization (FAO), 2016).
f. Enabling Institutional Environment (EIE) (Institutional functionality): Institutional functionality can impact an individual's capacity to deal with and respond to shocks and stresses. The overall idea is to use observable variables and individual perception as proxies for the latent-enabling institutional environment as a variable. For example, access to basic and important information, perceptions of the presence of services (for instance, extension services), and perception of the quality of such services; such that any reported access to services equals 1 and 0 otherwise. Meanwhile, perceptions of the presence of services, and perception of the quality of such services are usually conceptualized through ordinal ranking.
g. Sensitivity (SVTY): Incidence, Frequency, and the Intensity of shocks and stresses - (that is, single or repeated shocks occurring over a given period of time: for instance, illness).
h. Social Capital and Neighborhood Effect (SCNE)

   – Social group membership/social-networks accumulation (dummy).
   – Participation in collective action initiatives (Reciprocity and Trust) (dummy).

Quantile Treatment Effect Model Specification

The classical quantile regression represents an extended version of multiple regression (Debebe and Zekarias, 2020), and the model predicts that "*explanatory variables relate at different points of the dependent variable(s) and has a comparative advantage when errors are highly non-normal and hence automatically adjusted the non-normal errors and outliers data sets*." The feature described here is common to welfare differential analysis. More importantly, this technique permits to properly mirror the exact "*stochastic relationship between random variables*." The quantile regression model had also been previously applied by previous related welfare analysis studies such as, for instance, Fentaw and Appa (2016), Samuel (2017), Teka et al. (2018). Therefore, according to Samuel (2017), the quantile regression model is specified as:

$$Q_\tau \ln\left(\frac{Y_i}{X_i}\right) = x_i^{'}\beta_\tau + \varepsilon_{i,\tau}, \ . (3) \tag{3}$$

where: $Q_\tau \ln\left(\frac{Y_i}{X_i}\right)$ depicts the estimation of the model τ^{th} quantile Q_τ of the distribution of the dependent variable (Y), conditional on the value of explanatory variables (X).

$$\mathrm{Qln}\left(\frac{Y_i}{X_i}\right) = \sum_{i=y_i \geq x'\beta}^{N} q|y_i - X'\beta q| + \sum_{i=y_i \leq x'\beta}^{N} (1-q)\,|i - X_i'\beta q| \quad (4)$$

$$= \sum_{i=y_i \leq x'\beta}^{N} \left[(1-q)\,(y_i) \leq X_i'\beta\right]\left(y_i - X_i'\beta\right) \quad (5)$$

where: Y_i is the welfare status (in quintiles) of ith household, represents a column vector of realizations on k explanatory variables, and β is the column vector corresponding to unknown parameters $0 \leq q \geq 1$ is the quantile of interest.

Model Identification in Quantile Regression Estimates

As noted by Buchinsky (1998), the use of very few cross-sectional observations may present an issue toward model identification in the quantile regression analysis across predefined quantiles. For instance, the computed estimates will be spurious, and very imprecise, as well explained in Barnes and Hughes (2002); but this study used relatively large cross-sectional observations. Importantly, if the quantile regression is performed by using an aggregate welfare index (without delineating it into welfare quintiles), this may provide misleading inferences in terms of diversifying away from the contributions of each of the resilience pillars at varying levels of welfare quintiles, and may possibly dilute the impact of the quantile regression estimates.

In addition, the study is focused on the relative values of the resilience components parameters along the quintile categories, therefore, the absolute amount of bias should be of secondary concern, as emphasized in Barnes and Hughes (2002).

RESULTS AND DISCUSSIONS

This section describes the results and findings from the data generating process and its subsequent analyses. These are discussed as follows.

Distribution of Respondents by Well-Being Quintile

The results in **Table 1** revealed the distribution of respondents across the welfare quintiles estimated. The findings indicated that more than half (25% and 32.50%) of the respondents fall within the lowest (10th) and the second lowest (25th) welfare quintiles. Then, only 9.4% dcrease in the median quintile (50th). Meanwhile, 20.1% and 12.94% of the sampled respondents constitute the proportion of people who fall within the fourth (75th) and the fifth (90th) quintile classes. This evidently shows that most people in the study area are vulnerable to shocks.

TABLE 1 | Distribution of respondents by welfare quintiles.

Welfare Quintiles	Frequency	Percentage
First (0.1)	91	25.06
Second (0.25)	118	32.5
Third (0.50)	34	9.4
Fourth (0.75)	73	20.1
Fifth (0.90)	47	12.94
Total	**363**	**100**

Data analysis, 2021.

TABLE 2 | Cross-tabulation of Gender and Welfare Quintiles.

Welfare Quintiles	Gender		Total
	Male	Female	
First (0.1)	63 (26.47)	28 (22.4)	91
Second (0.25)	77 (32.35)	41 (32.8)	118
Third (0.50)	14 (5.88)	20 (16.0)	34
Fourth (0.75)	48 (20.17)	25 (20.0)	73
Fifth (0.90)	36 (15.13)	11 (8.8)	47
Total	238	125	363

Figures in parenthesis are percentage values.
Source: Data analysis, 2021.

Cross-Tabulation Profiling of Households' Specific Attributes and Welfare Quintiles

The cross-tabulation of the distribution of welfare quintiles by respondents' gender is shown in **Table 2**. The findings revealed that the majority of the respondents on both counts (male and female) constitute the bulk of the population of individuals who fall within the lowest (10th) and the second lowest (25th) welfare quintiles. However, very few of the male and female populations were found in the fourth (75th) and the fifth (90th) quintile continuum. This result agrees entirely with the findings discussed earlier in the previous table; a clear indication of the respondents' exposure, and perhaps vulnerability to shocks, stressors, and emergencies.

Effect of Resilience Indicators and Components on Farming Households' Welfare

The estimation of the quantile regression model as shown in **Table 3** revealed the magnitude and direction of movement of resilience pillars (driven by their respective indicators) on farming households' welfare status in the study area. The estimation also revealed that the model fit is good, and has pseudo R^2 ranging from 0.3216 to 0.5798 across all the quintiles (0.1, 0.25, 0.50, 0.75, and 0.90) (that is, 10th, 25th, 50th, 75th, and 90th) considered. Many of the resilience pillars were shown to have different directions of movement, and varying degrees

TABLE 3 | Quantile regression: effect of resilience indicators on households' welfare distribution.

	Dependent variable: Welfare Index									
	0.1		0.25		0.5		0.75		0.9	
Variables	**Coeff.**	***t*-value**	**Coeff.**	***t*-value**	**Coeff.**	***t*-value**	**Coeff.**	***t*-value**	**Coeff.**	***t*-value**
Quadr. Age	0.6786	2.40**	0.2473	6.51***	0.2103	3.08***	0.0095	2.64*	0.0558	1.3
Gender	−0.0744	−2.53***	−0.0513	−1.66*	0.093	2.16**	0.0064	0.2	0.0052	0.17
Family size	−0.0261	−3.21***	−0.3842	−2.14**	−0.2139	−1.65*	0.4228	1.41	0.0512	1.28
AST	0.0839	1.14	0.0346	1.58	0.2654	1.98**	0.1114	1.74***	0.034	1.93*
ACS	0.2521	0.62	0.0015	0.92	0.0402	0.29	0.1635	2.70*	0.009	1.71*
SSN	−0.2755	−1.68*	−0.086	−1.75*	0.0495	0.4	0.1551	3.24*	0.8781	3.40***
CC	−0.1775	−2.45**	−0.2791	−1.99**	−0.2844	−2.12**	0.0963	0.92	0.3048	1.63
ABSQ	0.2151	2.59***	−0.4767	−3.73***	−0.3399	−1.87*	−0.0476	−2.10**	−0.8186	−2.90***
EIE	0.0608	0.72	−0.1778	−3.49***	−0.0078	−0.98	−0.0229	−1.3	0.2175	0.64
SVTY	−0.101	−1.77*	−0.0326	−1.21	−0.0715	−0.58	−0.086	−1.75***	−0.3153	−3.83***
SCNE	−0.0017	−0.46	−0.0963	−4.51***	−0.9306	−3.89***	0.3572	2.94*	0.1898	1.86*

Food insecurity vis-à-vis food security status (FIS) was excluded from the model because of potential "multicollinearity" with the welfare variable.
****, **, * = $p < 0.01$, $p < 0.05$, $p < 0.1$ probability levels respectively.*
Source: Data analysis, 2021.

of statistically significant effect across quintiles of households' welfare status.

Specifically, the findings indicated that quadratic age has a direct and significant effect on households' welfare status at 10th ($p < 0.05$), 25th ($p < 0.01$), median-50th ($p < 0.01$), and 75th ($p < 0.01$) quintiles, respectively. This result has a strong link with the life cycle hypothesis in that, every increase in age induces higher households' welfare status, which is consistent along the welfare status continuums. All else equal, this result agrees with a-priori expectation and the findings of Muntaha and Matz (2015); because people in the "aged category" are likely to receive remittances and gifts from children, family members, and friends, as a gesture of societal and cultural values and responsibilities. Similarly, in line with Quisumbing et al. (2011), the gender of the respondent was found to have an inverse and significant effect on households' welfare status at 10th ($p < 0.01$) and 25th ($p < 0.1$), respectively. However, gender also has a direct and significant effect on households' welfare status at a slightly higher quintile (median-50th); a tenable explanation for this is that women are disproportionately poor compared to their male counterparts, hence the reason for the observed low welfare status among them; meanwhile, the positive and significant effect of the variable-gender at the median (50th) quintile pointed to the fact that there is a hope of transition from their present state to a better welfare status if they are equitably exposed to gender-just policies, and especially the social protection programs.

The estimation also indicated an indirect and significant impact of family size on households' welfare status at 10th ($p < 0.01$), 25th ($p < 0.05$), median-50th ($p < 0.1$) quintiles, respectively. Expectedly, this suggests that an increase in family size impacts negatively on households' welfare status, considering the lack of buffers and adaptive capacity, as well as the vulnerability of most people in the rural settlements of Nigeria. This finding is consistent with documented evidence in many extant studies.

The results in **Table 3** also indicated the dynamics of resilience pillars and indicators in building sustained households' welfare. For instance, possession of assets (AST) has a direct and significant impact on households' welfare at the same probability level ($p < 0.1$) but this significant effect was observed for median-50th, and higher (75th and 90th) quintiles only. This is expected, and further affirms the submission from notable literature (Quisumbing et al., 2011; Lokonon, 2017) that the more assets a household owns, the higher the likelihood of using the assets as buffers against any emergencies, shocks, and stresses.

More so, adaptive capacity and stability (ACS) were found to have a direct and significant impact on households' welfare status, only at higher quintiles [75th ($p < 0.05$) and 90th ($p < 0.01$)] respectively. This suggests that people who are in the higher quintiles of welfare status are the only ones who have the capacity to adapt and withstand shocks and stressors. More so, it is assumed that a household with high adaptive capacity will have a great level of resilience and higher welfare, but rural areas are characterized by low access to credit and a limited number of income sources, which push many households to lean toward friends, family members and networks to get assistance in-kind and cash, which obviously serve as buffers to respond to any shocks, stressors, and emergencies (Muntaha and Matz, 2015).

As far as the social safety nets (SSN) resilience pillar is concerned, with the exception of the median quintile, the study found both direct and inverse effects of social safety nets on households' welfare status across all quintiles: 10th ($p < 0.1$), 25th ($p < 0.1$), 75th ($p < 0.01$), and 90th ($p < 0.01$). This result is expected and agrees with the findings of Dillon and Quinones (2011) as well as Muntaha and Matz (2015) because benefitting from all kinds of social safety nets (for instance, receiving help from friends and relatives in the form of cash transfer and remittances, as well as government's social intervention and/or social protection programs) provides support for individuals, and cushion the effect of any episodes of shocks and stressors; and vice-versa.

Similarly, the findings also revealed an indirect and significant impact of climate change (CC) induced components or indicators on households' welfare status in the 10th 25, and 50th quintiles, respectively, all at ($p < 0.05$). The implication of this is that stable climatic condition enhances crop production, and sustained food availability, and by extension improves households' income and welfare. Apparently, any disturbance or shock in the climatic elements (especially rainfall) will negatively affect food production because agriculture in this part of the country is largely rain-fed dependent. The unfavorable situation (which also includes incidence of drought, soil erosion, and soil degradation) could weaken food availability and sufficiency, and equally puts households at a welfare risk. All of these can affect the capacity of a household to make a living, and respond to any shocks appropriately; hence, there is a need for social protection programs to reduce households' vulnerability to climate change induced episodes because of its consequential impact on households' welfare, irrespective of social class (Davis and Ali, 2014). It is important to stress that climate extreme events impact disproportionately on the people who are in the lower quintiles compared to those in the higher quintiles of households' welfare.

In a similar manner, access to basic needs/services and quality of services (ABSQ) as a resilience pillar and components revealed both a direct and inverse association with households' welfare at all levels of welfare quintiles, though with varying degrees of probability levels [(10th ($p < 0.01$), 25th ($p < 0.01$), 50th ($p < 0.1$), 75th ($p < 0.05$), and 90th ($p < 0.01$)]. Judging from the estimates, access to basic needs/services and quality of services has a direct impact on households' welfare status at the lowest welfare quintile (10th) only, while it has an inverse relationship with households' welfare status at other welfare quintiles. Basically, access to basic services has been touted as a fundamental aspect of resilience building; such as good roads, schools, health care centers, water, electricity, and nearby markets. For instance, access to markets, and the efficacy of aid distribution in response to emergency situations are directly and indirectly influenced by the density of the road network. Notable evidence supports the relationship between access to basic services before emergencies and the recovery rate after an emergency situation (Khan, 2014).

Similarly, access to basic services is pivotal to determining an individual's risk of exposure; for instance, the risk of illness is often associated with inadequate waste disposal, poor water supplies, and sanitation issues (Dercon et al., 2004). Likewise, poor institutional performance often leads to the total neglect of the important areas like housing, healthcare, and sanitation; which consequently lead to inefficient responses to emergencies and shocks. All in all, poor access to basic and quality services can be detrimental to households' livelihood and income generating activities, and also block the pathway to building improved households' welfare and prosperity.

With respect to enabling institutional environment (EIE), the findings also indicated a negative and significant ($p < 0.01$) relationship with households' welfare, but this relationship only expressed itself at a low welfare quintile (25th). This is to say that institutional functionality in the study area (in terms of (seamless access to information, and good and quality service delivery) is absent or very poor to the extent of having a spill-over effect on households' welfare. In the same vein, sensitivity components have an inverse and significant relationship with households' welfare status at 10th ($p < 0.1$), 75th ($p < 0.1$), and 90th ($p < 0.01$), suggesting that increase in the incidence, frequency and the intensity of shocks and stressors induces negative impact on households' welfare status. Suffice it to say that repeated episodes of shocks (for instance, illness, drought, pandemic, etc.) occurring over a given period of time diminishes people's ability to cope and adapt to shocks, disproportionately (Dercon, 2010).

In terms of social capital and neighborhood effect (SCNE) as a resilience pillar/component, the results indicated a significant and inverse relationship with households' welfare at low (25th) and medium (50th) quintiles, respectively, both at $p < 0.01$ significant level; while this same component also has a direct and significant impact on households' welfare at 75th ($p < 0.01$) and 90th ($p < 0.1$) welfare quintiles. The implication is that most people who fall within the lowest to the medium quintiles do not appropriately use their social networks; perhaps their local level institutions are largely for social gatherings/events. Conversely, the people who fall to the higher welfare quintiles (75 and 90th) appear to judiciously utilize their stock of social networks, connections, and neighborhood effects, in benefitting each other; although this can equally be attributed to the comparative advantage of social class these people enjoy.

From the aforementioned, the findings revealed the importance of resilience pillars in achieving sustained households welfare. Meanwhile, the effectiveness of these important resilience pillars (capital assets, adaptive capacity, social safety nets, climate change adaptation, access to basic services and quality of service, sensitivity as well as social capital and neighborhood effect) in building buffers against shocks is dependent on enabling institutional environment which clearly mirrors institutional functionality in terms of adequate extension delivery systems, sound and viable policy implementation for rural economic development. In essence, extension and advisory services in rural areas are challenging even under normal circumstances, let alone under unfavorable situations and obvious challenges. If these challenges are to be adequately addressed, extension service delivery should be able to aid in enhancing the resilience of farmers in several ways, such as coordinating bodies for multiple support organizations as well as providing more relevant services at various stages of a shock because of its linkages with the local environment, and as a result of its potential access to timely information, extension system is able to identify relevant actors with whom to work to ensure those intervention strategies are harmonized, relevant, effective, and timely.

Another important path through which extension delivery service could enhance resilience building is by providing information and knowledge on climate extreme events, market prices, regulatory structures, and consumer demands so that farmers can make timely informed decisions. Such functional extension delivery systems could also assist in identifying the most vulnerable households that can be easily impacted by shocks, so as to develop a proper register of the vulnerable population to be targeted for interventions. In fact, this will go a long way to assist Nigeria with a credible register and database of the vulnerable population. It is important to stress that the effectiveness of the highlighted areas where extension services could be useful is critically dependent on the funding, organization, and implementation of the extension system and policies in Nigeria. In formulating policies, caution must be taken to avoid a situation where policies designed to achieve a positive goal unintentionally cause deterioration of individual or community resilience.

CONCLUSION AND POLICY STATEMENTS

The resilience assessment of a given food system can only be achieved through a synthetic indicator conceptualized through the resilience tools. Understanding system dynamics, highlighting strategic issues, and identifying and understanding the strength and weaknesses of the system may require both qualitative and quantitative knowledge. Therefore, this study explored the synergies between the components/indicators of resilience and households' welfare distribution in the study area. This study has shown that the majority of the people in the study area are vulnerable to an episode of shocks and stressors without any sustainable buffer options which can be attributed to their limited capacity across all the pillars and indicators of resilience.

The study also revealed that households are at a welfare risk, and find it difficult to build sustained resilience against shocks and stresses; any disturbance and shock in terms of climate-induced extreme events will obviously have untold hardship on households. Apparently, stable climatic condition enhances crop production, builds sustained food availability, and by extension improves households' resilience and welfare status. Then, all kinds of social safety nets (for instance, receiving help from friends and relatives in the form of cash transfers and remittances, as well as government's social intervention/investment programs, etc.) provide support for individuals and cushion the effect of any episodes of shocks and stressors.

Conclusively, the majority of the sampled respondents are lacking across all the major pillars and components of resilience, which renders them vulnerable to shocks and stressors. There is a need for social protection programs to reduce households' vulnerability to shock and stressors. There is a need for investments to be made across all pillars and indicators of resilience to build an improved and sustained households' resilience capacity, and welfare status across all social strata.

SPECIFIC CONTRIBUTIONS TO KNOWLEDGE

This study has contributed to several existing literature on resilience building against shocks and stressors in Nigeria by addressing the gaps identified in the previous related studies in Nigeria. While there is a paucity of studies in Nigeria addressing resilience as a concept through its fundamental pillars and corresponding indicators, many of the available related studies did not give a clear conceptualization of resilience as outlined by FAO. More so, given that welfare appears increasingly stochastic, and can be influenced by various exogenous factors, this study delineated aggregate welfare index into welfare quintiles to be able to show the contributions of each of the resilience pillars at varying degrees of welfare quintile, which to the best of our knowledge is not absolutely considered in any of the previous related studies in the study area.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee, Department of Agricultural Economics, Ladoke Akintola University of Technology, Ogbomoso, Nigeria. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SO conceptualized and designed the study. He developed the introduction, research design and methodology. He was involved in the collection, coding and cleaning of the data, and also carried out the data analyses, and he read, reviewed and approved the draft manuscript. TO developed the literature review, and assisted in the data collection activities. She was also involved in the data analysis, and she read, reviewed and approved the draft manuscript. OI also developed part of the literature review, and assisted in the data collection activities. He was involved in the data analysis, and he read, reviewed and approved the draft manuscript. OO assisted in the collection of data, coding and cleaning of the data and data analysis. He also read and approved the draft manuscript. All authors contributed to the article and approved the submitted version.

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Could microalgae offer promising options for climate action via their agri-food applications?

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In 2021 the Intergovernmental Panel on Climate Change (IPCC) issued the first volume of its latest authoritative report on climate change. Underlining the seriousness of the situation, the United Nations Secretary-General branded its findings a "code red for humanity." The need for climate action is now evident, but finding viable pathways forward can be elusive. Microalgae have been attracting attention as a category of "future food," with species like *Arthrospira platensis* (spirulina) and *Chlorella vulgaris* (chlorella) seeing growing uptake by consumers while research interest continues to expand. One timely but neglected question is whether microalgae might offer options for promising climate actions via their agri-food applications. Specifically, might they offer scope to help secure food supplies, while also providing climate resilient livelihood pathways for vulnerable farmers already grappling with food insecurity and environmental degradation? This paper reports on a review of the academic literature on microalgae as an agri-food technology, notably their uses as a food, feed, biofertilizer, biostimulant, and biochar. This family of applications was found to offer promising climate actions vis-à-vis both mitigating and adapting to climate change. Aspects pertinent to adaptation include growing rapidly under controlled conditions, reusing water, providing potent nutrition for humans and animals, and supporting resilient crop production. Agri-food applications of microalgae also provide opportunities to mitigate climate change that could be explored. The paper concludes by flagging possible risks and obstacles as well as research and policy priorities to elaborate and harness this potential.

KEYWORDS
climate change, food supply, small-scale farmers, agri-food technologies, future foods, microalgae, climate resilience, climate change mitigation

Introduction

What does the "code red for humanity" mean for food and agriculture?

United Nations Secretary-General António Guterres branded the latest authoritative report by the Intergovernmental Panel on Climate Change (IPCC) a "code red for humanity." Responding to its findings, he said, "The alarm bells are deafening, and the evidence is irrefutable... putting billions of people at immediate risk. If we combine forces now, we can avert climate catastrophe. But... there is no time for delay and no room for excuses" (UNRIC, 2021).

The emerging and predicted impacts on agriculture and food supplies are stark (Table 1).

Sky-high rates of climate anxiety among young people underline the gravity of climate change (CC). A recent survey (Thompson, 2021) asked 10,000 16–25 year-olds from 10 countries how they felt about CC. It found nearly 60% felt "very worried" or "extremely worried" about it, while 45% said these feelings affected their daily lives, due in part to a sense that governments aren't doing enough to avoid catastrophic outcomes. Similarly, a climate scientist reported that the top five questions she has been asked on TikTok regarding CC are: Is it too late? Should I go to college or will the world end by then? Am I a bad person for having a child? Will we run out of food and water soon? How can I help as an individual with no power? (Wood, 2022).

Agriculture as a source of CC response options

While agriculture is clearly impacted by CC, it is also a key cause of CC and offers various potential response options. When talking about agriculture as a locus of CC mitigation options, the IPCC groups it together with forestry under the heading "agriculture, forestry, and other land uses" (AFOLU). The AFOLU sector is currently responsible for 13–21% of the anthropogenic greenhouse gas (GHG) emissions causing CC, and key contributing activities include deforestation, enteric fermentation from ruminants, and soil fertilization effects. At the same time, the AFOLU sector offers significant near-term CC mitigation potential at relatively low cost, and these CC mitigation measures can potentially also deliver multiple co-benefits including food security (IPCC, 2022c).

In short, some agricultural practices and technologies could be termed "climate smart." Climate-smart agriculture has been defined as a family of technological options that can simultaneously address three objectives, namely increasing farm productivity and incomes, adapting and building resilience to CC, and mitigating CC. As such, climate-smart agriculture offers scope for "win-win" outcomes (FAO, 2013). Emerging critiques suggest however that this optimistic narrative can mask difficult questions like how any trade-offs are managed and who decides this (Ellis and Tschakert, 2019).

Various proven climate-smart agriculture practices have already been identified, but given the magnitude of the CC threat all promising technologies should be explored. Notably, innovative options are needed to permit a step change vis-à-vis food and agriculture. The United Nations Food Systems Summit (United Nations, 2021a) in September 2021 was premised on such a need for fundamental change. Its vision was to support the United Nations Sustainable Development Goals by fostering tangible changes to food systems, building on extensive consultations with stakeholders around the world.

Agri-food uses of microalgae as possible climate response actions

Algae are already attracting attention as a possible basis of climate action, but the focus to date has primarily been macroalgae, or seaweeds, rather than microalgae, notably on their potential contributions to CC mitigation (Seaweed Climate, 2022). For instance, seaweeds were discussed at the high-level CC conference in November 2021 (COP 26, 2021) in the context of the Global Methane Pledge (2021), which seeks to rapidly reduce methane emissions by advancing technical and policy work. This follows evidence that using seaweeds as feed supplements can sharply lower enteric methane emissions from cattle (Kinley et al., 2016; Makkar, 2018; Mihaila et al., 2022).

Microalgae are a diverse group of microscopic aquatic organisms that can be either single-celled or multicellular. Like plants, they typically generate energy from sunlight via photosynthesis, but they differ from plants in basic ways. One example is growing in fresh, brackish or sea water instead of on land, while another is absorbing nutrients from their substrate instead of via roots (Petersen et al., 2021). Some microalgae are seen as harmful, such as those that cause algal blooms which kill aquatic organisms (Shaw et al., 2003), while others can provide or serve as feedstocks for useful products like dyes, biofuels, or bioplastics.

Some microalgae uses involve food and agriculture, and may be termed agri-food technologies. This includes using microalgae as human dietary supplements, livestock feeds, or means to foster "climate smart" cropping via products like biofertilizers, biostimulants, and biochar.

One critical difference between macroalgae and microalgae stems from how they are produced. Microalgae are grown in either ponds or enclosed tanks, and hence as an inland crop. By contrast, macroalgae are typically either harvested from or farmed in the sea. While macroalgae can also be grown in ponds or tanks (Mata et al., 2015), such facilities must be situated on or near the coast. The fact that microalgae can grow inland

TABLE 1 Selected quotations from relevant sections of the latest IPCC report (IPCC, 2022a,b).

Theme	Selected quotations
Impacts on agriculture	• Climate change (CC) results in more frequent heat waves, extreme rainfall, drought, and rising sea levels, which negatively affect crop yields • CC will increasingly expose... animals to heat stress, reducing... dairy and meat production • CC has already... increased variability of rainfall... • Increased soil salinity... [is] among the most common effects of CC in irrigated regions
Implications for food security	• CC impacts are stressing agriculture... increasingly hindering efforts to meet human needs • Impacts on food availability and nutritional quality will increase the number of people at risk of hunger, malnutrition and diet-related mortality... • Increased, potentially concurrent climate extremes will periodically increase simultaneous losses in major food-producing regions.
Particular risks to vulnerable groups	• Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate CC • Global hotspots of high human vulnerability are... Africa, South Asia, Central and South America, Small Island Developing States and the Arctic • CC impacts everybody, but vulnerable groups such as...small-scale producers, are often at higher risk • CC is... increasingly driving displacement in all regions...
Significance of climate actions	• Effective adaptation options... enhance food availability and stability and reduce climate risk for food systems while increasing their sustainability • For 127 identified key risks, ... mid- and long-term impacts are up to multiple times higher than currently observed, [yet their] magnitude... depends strongly on near-term mitigation and adaptation actions.

means they can be produced diverse locations, and might thus serve as the basis of climate actions in a wide range of contexts. Microalgae production systems typically rely on photosynthesis, but recent technological developments also allow cultivation in the dark via heterotrophy (Linder, 2019). Still another possibility is producing microalgae via mixotrophy, which is a combination of these two strategies (Tibbetts, 2018).

This review considered whether agri-food uses of microalgae might offer options to help society face the looming CC threat, and hence represent a fruitful focus area for intensified research and development efforts. This study question stems from the urgent need faced coupled with encouraging early evidence on these technologies.

One demographic that is emphasized by this paper is small-scale farmers in the Global South, given their elevated vulnerability to CC, notably threats to their farming operations and food security. Critically, farming is the primary livelihood for many of the world's poor, while agricultural development is central to addressing development goals like ending poverty and achieving food security. It is estimated that 590 M of the world's 656 M farms are family farms, of which 551 M are small-scale (<2 ha; Erenstein et al., 2021). Such small-scale farmers are a key focus of international development efforts. The numbers of undernourished people are higher still due to also including many working in other sectors. Namely, 768 M people worldwide are undernourished of which 700 M live in Africa or Asia, while 2.37 B are unable to access adequate food year-round (FAO, 2021).

Charting climate resilient livelihood pathways for these populations is important not just for them but also others, given predictions of sharp rises of climate refugees from such areas under current trends (IPCC, 2022d), which could prove difficult for both migrants and recipient countries (Krieger et al., 2020). This paper thus specifically considers whether the technologies it examines may offer pertinent resilience building options for such communities.

Methodology

The study question was investigated via a systematic review of the academic literature conducted using the Web of Science and Google Scholar.

The literature search began by using the term climate change in combination with the terms microalgae, spirulina, chlorella, resilience, food, feed, and livestock, which delivered 191 papers. Scanning these for relevance to the study question gave 63 pertinent papers, while excluded papers addressed themes like microalgae as a biofuel or impacts of CC on natural microalgae populations. This search was supplemented by the 70 papers delivered at the AlgaEurope conference in December 2021 (AlgaEurope, 2021).

Due to insufficient evidence obtained on three key agri-food applications of microalgae, supplementary searches on biofertilizers, biostimulants, and biochar were also conducted. These searches were broadened by excluding the term climate change. Relevant studies cited by the various papers identified were also incorporated into this review.

Analysis of these papers involved grouping them then distilling their findings under target themes. The potential of each agri-food use of microalgae to help meet both of the key climate action objectives—CC mitigation[1] and CC adaptation[2]—was then explored, since viable options are needed in both these domains. The scope for microalgae to help build climate resilience—a form of CC adaptation—was emphasized, given the importance of resilience considerations for both farmer livelihoods and food supplies. A conceptual framework was also proposed on the potential future role of such technologies as CC response options. Finally, risks and obstacles were highlighted then research and policy priorities were flagged.

Results

The following subsections share results for the five agri-food applications examined, with biofertilizers and biostimulants being combined due to overlaps in the literature on these technologies. One overarching finding was that many of the papers reviewed reported evidence on microalgae and their agri-food applications that is directly relevant to the objectives of climate action, namely CC mitigation and/or CC adaptation (Figure 1). For the most part, however, these papers did not highlight these linkages or frame these technologies as potential bases for climate action. Given this apparent disconnect, two further searches were conducted to elucidate these dynamics. The mitigation and adaptation volumes of the 2022 landmark CC report were also searched (IPCC, 2022f). Microalgae was mentioned four times, of which two involved possible agri-food uses as a climate action, specifically microalgae as an alternative protein source for livestock or aquaculture. Finally, the 191 Nationally Determined Contributions (NDCs), or national climate action plans, submitted by governments as the basis of their Paris Accord commitments were searched, and no mentions of microalgae were found (United Nations, 2021b). In short, it seems that researchers and practitioners alike are largely failing to make these connections at present. Possible explanations include the body of relevant evidence being thin, most studies being recent, and mapping such linkages requiring input from different disciplines and an interdisciplinary perspective.

1 "A human intervention to reduce the sources or enhance the sinks of GHGs..." (IPCC, 2014).

2 "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities..." (IPCC, 2014).

Microalgae as food supplements

Microalgae have been used as traditional foods in various countries where suitable species occur naturally. For instance, spirulina was harvested from lakes for use as a food by the Aztec civilization of Mexico (Ciferri, 1983), while communities living nearby Lake Chad in Africa still harvest spirulina from its waters (Abdulqader et al., 2000). The ancient Maya are believed to have both cultivated spirulina as a food and incorporated it into crop irrigation waters (Piccolo and Short, 2014).

Contemporary production of microalgae is dominated by two species—spirulina and chlorella—that account for 80% of estimated global production at 15,000 and 5,000 tons/year, respectively (Ciani et al., 2021). Besides these two, only a few other species are authorized for use as food in key jurisdictions like the European Union and United States (Ciani et al., 2021).

In addition to being the most widely produced microalgae, spirulina (*Arthrospira platensis*) is a key focus of published research on agri-food applications of microalgae (Habib et al., 2008), so the reported findings focus largely on this species.

Microalgae food supplements are principally eaten by health-conscious consumers, but can also be used to help address malnutrition and improve health in places where diet is poor (Piccolo, 2011). They can be sold as a dry powder or capsules, or incorporated into food products to boost their nutritional profile (Gantar and Svircev, 2008). Examples of studies on such products include pasta (Fradinho et al., 2020), baked goods (Uribe-Wandurraga et al., 2019), and sweetened snacks (Batista et al., 2017).

Microalgae can be potent sources of various nutrients, including high-quality proteins, lipids, and vitamins.

Some microalgae species are protein-rich, such as spirulina and chlorella. At 45–65% of dry weight biomass, spirulina has a protein content that is two times higher than beef, pork, or poultry, four times higher than eggs, and 1.5 times higher than soy (Ciani et al., 2021). A key determinant of protein quality is its amino acid profile. The essential amino acids are especially important, since they are not produced by the human body and hence must be obtained from food (Damodaran et al., 2007). Some authors suggest that microalgae can contain all the essential amino acids (Wells et al., 2017), while others report examples of microalgae supplying most but not all of the essential amino acids, such as *Chlorella vulgaris* being deficient in isoleucine (Amorim et al., 2021).

Digestibility is another important consideration, though findings differ between studies. Machado et al. (2022) suggest that microalgae cell walls could affect their digestibility and bioaccessibility without prior processing, but specify this does not apply to spirulina. Acquah et al. (2020) report that pre-treating microalgal biomass is important prior to using it as a food due to poor digestibility (Acquah et al., 2020). Niccolai et al. (2019) examined the digestibility of crude protein from several microalgae species and the values obtained for spirulina

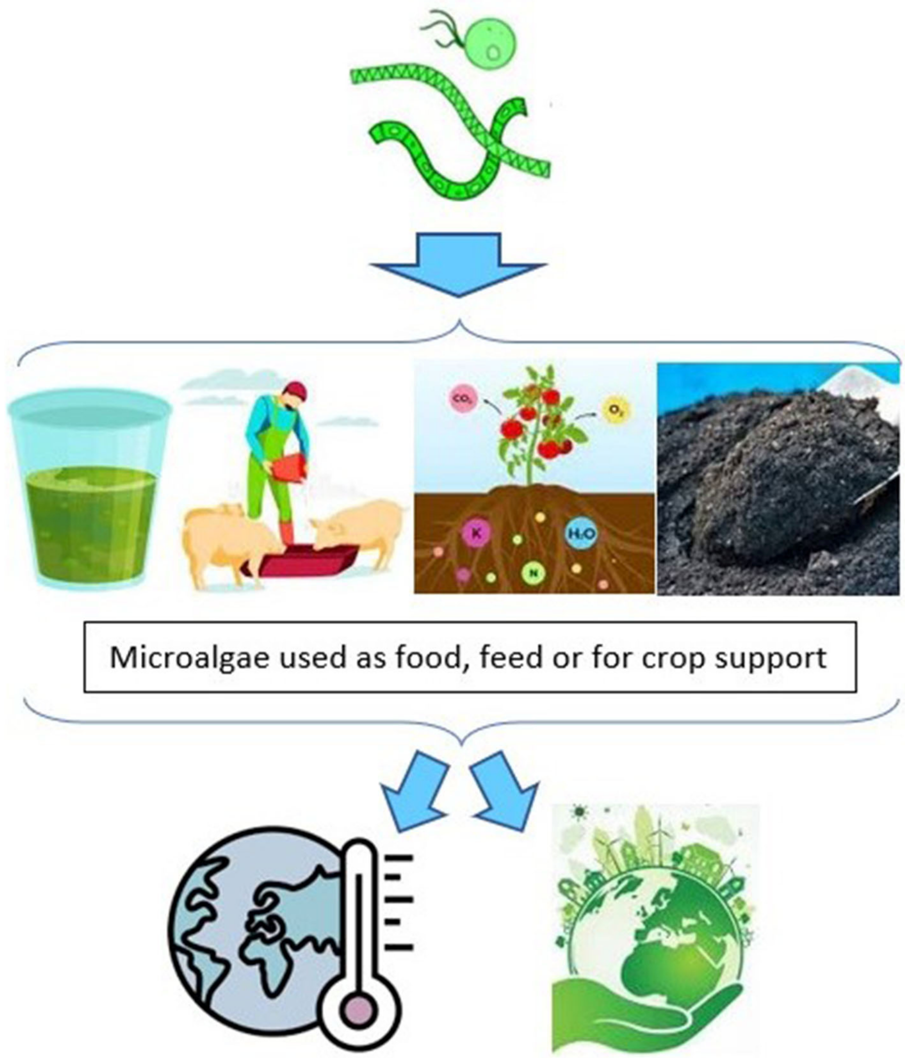

FIGURE 1
Agri-food applications of microalgae can potentially contribute to CC mitigation and/or CC adaptation objectives.

and chlorella compared favorably with the values for established human foods like beans, oats, and wheat.

Lipids are essential to all living organisms for membrane formation, energy storage, and cell signaling (Eyster, 2007). Although humans and other mammals synthesize lipids, some essential lipids must be obtained from diet, notably the long-chain polyunsaturated fatty acids (PUFAs; Holdt and Kraan, 2011). Microalgae like spirulina and chlorella are good sources of some PUFAs, such as linoleic acid (an omega 6 fatty acid) and α-linolenic acid (an omega 3 fatty acid), but less effective as sources of some other PUFAs (Wells et al., 2017). Microalgae may offer a sustainable means to obtain essential fatty acids amidst fears fish stocks are being depleted (Merz and Main, 2014; Morao et al., 2021).

Vitamins are micronutrients needed for essential metabolic functions that must be obtained from diet since organisms cannot synthesize them in sufficient quantities (Wells et al., 2017). Vitamin deficiencies, meanwhile, can lead to diseases like beriberi, pellagra, and scurvy (Stabler and Allen, 2004; Martin et al., 2011). Microalgae are rich in vitamins. For instance, spirulina has been found to be rich in vitamins A, B1, B2, B12, and E (Becker, 2013), while Chlorella is a good source of vitamin B12 (Watanabe et al., 2002).

In addition to their nutritional value, there is growing evidence on the scope for microalgae to serve as functional foods or nutraceuticals. These are defined as foods that contain bioactive compounds or phytochemicals that may benefit health beyond basic nutrition (Wells et al., 2017; Kholssi et al., 2021). Such studies might examine potential anti-inflammatory, antibacterial, antioxidative, antiviral, hypolipidemic, and/or anti-carcinogenic activity associated with microalgae consumption (Hosseini et al., 2013; Qinghua et al., 2016). This work, however, falls outside the scope of the present review.

Microalgae as a family of crops

Most microalgae produce biomass via photosynthesis using carbon dioxide (CO2), nutrients and light. Some species including chlorella can also grow heterotrophically (i.e., in the dark) via chemical processes. This can deliver much higher yields than production via photosynthesis, namely 150–200 vs. 5–10 g/L of dry biomass (Ciani et al., 2021). Recent technological developments make it possible for microalgae to be commercially produced via heterotrophy, but for the moment most production still relies on photosynthesis (Linder, 2019; Ciani et al., 2021).

In nature, spirulina can be found growing in marshes, lakes, seawater and thermal springs. It grows best under bright sunshine in alkaline (pH 8.5–11) and saline water (ideally 20–70 g/L but up to 270 g/L) and at elevated temperatures (35–37°C; Habib et al., 2008). These properties help limit the risk of biotic contaminants, since other microorganisms may struggle to survive under such conditions (Kebede and Ahlgren, 1996). For instance, it thrives in highly alkaline, saline lakes in Africa's Rift Valley, where it strongly dominates other microalgae populations (Habib et al., 2008).

Spirulina production currently falls into two broad categories: Commercial operations supplying the health food market and initiatives to bolster food security in developing countries. It can be produced using expensive equipment like photobioreactors with precise parameter control systems. Alternatively, simple technologies can be used like unlined ditches, rudimentary stirring devices, harvesting with cloth and drying in the sun (Habib et al., 2008). Production operations could also use intermediate technologies like PVC-lined culture ponds stirred by electrically driven paddle wheels (Piccolo and Short, 2014). The quality control of the algal biomass produced via simple systems will be lower, potentially raising questions about its suitability as a food. Alternatively, such algal biomass could perhaps be used for other agri-food applications for which quality standards are less stringent.

At present microalgae is generally produced in open ponds under natural light, but it can also be produced under artificial light. As things stand this imposes additional costs but solar PV costs continue to plummet (IRENA, 2022), which could make this option economically competitive in time for microalgae uses like food. The benefits of using artificial light include greater independence from weather conditions and continuous operation throughout the day and year. By facilitating use of closed production systems, artificial light also creates scope for providing higher and more constant biomass quality (Ciani et al., 2021).

Microalgae production can be much more efficient than growing crops or raising livestock, since it occurs under controlled conditions that foster efficient nutrient utilization and stable, rapid growth, while also having low land and water demands and not requiring pesticides or antibiotics (Tredici, 2010). This is reflected in comparisons of securing dietary protein via different foods, notably estimates of inputs required and environmental impacts imposed (Ciani et al., 2021). The protein production per unit land (kg/ha/year) of spirulina was 500x more than beef, 60x more than pork, 15x more than poultry, and 5x more than soybeans. Water requirements per kg protein from spirulina were comparatively low, namely 0.7–3% of beef, 1.5–5% of pork, 3–10% of poultry, 2–9% of eggs, and 13–50% of soy. GHG emissions per kg protein of spirulina were likewise comparatively low, namely well below 1% of beef, 5–12% of pork, 8–12% of poultry and 8–11% of eggs (Values for soy were not provided.).

An FAO report (Habib et al., 2008) on spirulina as a food or feed set the stage for the current review. It observes, "spirulina appears to have considerable potential for development... as a small-scale crop for nutritional enhancement, livelihood development and environmental mitigation." It laments that spirulina "has not yet received the serious consideration it deserves as a potentially key crop in... areas where traditional agriculture struggles" due to factors like "salination and water shortages," especially given the "impacts of global CC." It suggests that governments and international organizations should reassess the potential utility of spirulina as an alternative crop, notably in "communities where the staple diet is poor or inadequate." This report did not however explore the ways that spirulina might help deliver on CC objectives. Another FAO report (Piccolo, 2011) suggests producing spirulina to serve markets like health conscious consumers and institutions supporting food insecure populations offers an attractive business opportunity, since this can be done with a modest investment while the needed technical expertise is simple to obtain.

Is microalgae cultivation climate resilient?

Various authors list distinguishing characteristics of microalgae cultivation as part of their analysis. These are sometimes framed as key advantages of such cultivation relative to conventional crop or livestock production. Table 2 shares characteristics cited by several papers analyzed for this review.

Taken together, these characteristics could be seen as different ways in which microalgae production is resilient to

TABLE 2 Characteristics of microalgae production flagged by different authors.

References	Quotations from selected papers
Habib et al. (2008)	It does not require fertile land and can actually benefit from saline conditions. It also uses less water per kilogram of protein than other crops, and water can be recycled such that the only significant water loss is through evaporation.... Its production can be conducted at... different scales, from household "pot culture" to intensive commercial development over large areas.
Chia et al. (2020)	Microbial protein production does not directly compete with crop-based food commodities for fertile soil and freshwater and can be located in marginal lands and in industrial or metropolitan areas... [It] is much more efficient than cultivating plants in an open field or raising animals, owing to the stability of growth parameters, efficient utilization of nutrients, low water and land footprint, and no need for pesticides or antibiotics.
Halmemies-Beauchet-Filleau et al. (2018)	The major advantages of single-cell proteins [like bacteria, fungi or microalgae]... are the independence of production from arable land and of weather conditions as well as the high and continuous harvests.
Sills et al. (2021)	The beneficial impact derived from replacing conventional animal feed with... algae results primarily from avoiding land use and fresh-water consumption to cultivate crops. Soy and corn use much more land than algae due to algae's high areal productivity, and ability to grow on non-arable land. Using renewable electricity can improve the environmental performance of algal biorefineries.
Walsh et al. (2015)	Microalgal strains and growing conditions can be selected or engineered to match varying climatic conditions and commodity demands. Algacultural production systems can be constructed on degraded or otherwise unproductive land... Many strains grow in brackish or seawater, and freshwater can be recycled through many harvests, thus minimizing... freshwater use... Finally, CO2 can be supplied from flue gases or drawn directly from the atmosphere in open systems.
Linder (2019)	At a time when... food production... is threatened by... CC, the production of edible microorganisms has the potential to circumvent many of the current environmental boundaries of food production... [while also] reducing its environmental impact.... If... conditions are favorable and nutrients are abundant, some microorganisms are capable of very rapid growth.
Amorim et al. (2021)	Algae farming can be performed on lands with soil, water or climate that are not suitable for conventional crops which may allow the production of food and energy in regions wherein people are experiencing hunger.
Sanyal et al. (2020)	Growing green microalgae could be a great option for fixing CO2 by photosynthesis as it can be grown on non-arable lands... Several algae species are able to grow in wastewater... an available source of water with necessary nutrients for algae cultivation.

stresses and shocks. Critically, the technological profile they evoke seems well-suited to boosting the climate resilience of production, or enhancing the scope to deliver dynamic production despite climatic shocks. Still another characteristic of microalgae that supports the contention that it can help build climate resilience is their capacity to evolve quickly to adjust their biology to stresses like elevated temperatures and ultraviolet radiation (Wong et al., 2015; Padfield et al., 2016).

According to the IPCC, climate resilience is defined as "The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding, or reorganizing in ways that maintain their essential function, identity and structure" (IPCC, 2014). For perspective on climate resilience priorities for agriculture and food supplies, see Table 1 on the different ways CC threatens agriculture.

Table 3 distills the main characteristics of microalgae repeatedly evoked in this literature, then highlights their linkages to fostering climate resilient farming and food supplies.

Microalgae as livestock feeds

Livestock production is key to the human food system, with animal-sourced foods like meat and dairy key parts of diet in cultures across the world, notably as a source of protein. Moreover, livestock can transform substances inedible to humans like grasses or food waste into nutritious, palatable foods (Halmemies-Beauchet-Filleau et al., 2018). Livestock is also a key source of rural employment and savings and can be central to culture, particularly in the developing world (Dumont et al., 2018; Chia et al., 2020).

A key challenge facing this sector is sustainably securing ample and nutritious livestock feed. Feed is a particular problem in parts of the tropics, where forages often have poor nutritive value including low protein content, which limits the efficiency of animal production (Halmemies-Beauchet-Filleau et al., 2018). Yet feed demand is expected to continue rising strongly, particularly in developing countries (Chia et al., 2020). Securing feed is estimated to account for 60–70% of livestock production costs (Chia et al., 2020), with meeting the protein needs of animals a particular concern (Amorim et al., 2021). Proteins are needed for key physiological and biochemical processes such as those by which dairy cows convert feed into milk (Hof et al., 1994).

Feed supply concerns dovetail with CC concerns in two distinct ways.

Feed insecurity is an emerging concern among livestock keepers that is linked to CC (Cordeiro M. R. C. et al.,

TABLE 3 Key characteristics of microalgae flagged in the papers reviewed and their linkages to climate resilience.

Characteristic	Description	How it builds climate resilience
Temperature tolerance	Some microalgae tolerate elevated temperature, e.g., 35–37°C is optimal for spirulina	Higher average temperatures is a key CC impact, so crops that tolerate this should cope better
Controlled water supplies	Cultivation systems like tanks or ponds have controlled water supplies, so cultivation does not rely directly on local weather patterns	Water scarcity and erratic rains are key CC impacts, but evaporation of culture medium can be limited and water can potentially be reused
Coping with degraded land	Microalgae grows in aqueous medium. Hence It does not require arable land and can be grown on degraded, salinized or contaminated lands	Land degradation exacerbates CC vulnerability, since it lowers soil fertility and water-holding capacity. Microalgae is not affected by this
Efficient land use	Microalgae can be produced in small spaces due to growing fast in aqueous medium, potentially including extending production vertically	CC threatens agriculture so securing higher productivity in areas that are still producing could help compensate for any shortfalls
Lower pest and disease risks	Microalgae culture avoids many pests and diseases but may be vulnerable to aquatic pathogens	CC can aggravate pest and disease risks to crops and livestock, so averting these reduces risks

2022). CC can adversely affect feed supplies by threatening the quantity and quality of pastures and feed crops, thus hampering livestock production or even causing animal deaths. Maluleke and Mokwena (2017) report that livestock in South Africa are highly vulnerable to CC due primarily to adverse effects on feed supplies, while Catley et al. (2014) found that elevated livestock mortality rates in Ethiopia were due primarily to starvation or dehydration linked to climatic effects.

Meanwhile, steps taken to secure feed can increase GHG emissions and thus aggravate CC, notably where this involves converting forests to pastures or cropland for feed crops. Clearance of forest to produce feed crops like soya is the main cause of global deforestation, and two-thirds of forest losses in Brazil involve conversion to pastures (Guéneau, 2018). A related source of GHG emissions is transporting feed to its target users. For instance, ruminant milk and meat production in Europe relies largely on imported soya from distant South America (Lindberg et al., 2016). Livestock are estimated to account for 14.5% of total current GHG emissions (Gerber et al., 2013), making it a key cause of CC, though a more recent analysis suggests this may be an underestimate (Xu et al., 2021).

Novel feeds like microalgae (Lamminen et al., 2017), seaweed (Makkar et al., 2016), bacteria (Halmemies-Beauchet-Filleau et al., 2018), and insects (Van Huis et al., 2015; Shah et al., 2022) offer options to improve the sustainability of livestock production. They can provide environmentally friendly protein-rich feed supplements that complement staple feeds like grasses and feed crops. Moreover, they can do so without compromising the quality of animal products, and may actually improve the quality of products like meat (Meale et al., 2014) and milk (Boeckaert et al., 2008).

Microalgae have been flagged as especially promising future livestock feeds, despite their minimal use at present (Halmemies-Beauchet-Filleau et al., 2018).

Microalgae have been tested in feed formulations for cattle, goat, sheep, pigs, poultry and fish, and results have typically included higher productivity and/or better nutritional quality of products (Amorim et al., 2021). Such feeds also provide avenues to face the looming climate threat, including both adapting to and mitigating CC.

Using microalgae as feed supplements offers scope to enhance the climate resilience of livestock production in two distinct ways. First, it could ensure access to protein supplements thanks to the fact that production of microalgae biomass seems likely to be climate resilient, as discussed in Section Is microalgae cultivation climate resilient?. Second, this feed could have positive effects on animals that may enhance their capacity to cope with CC impacts. Notably, it can improve the digestive function of ruminants—including rumen-based protein synthesis—thus enhancing animal performance given available feed resources (Halmemies-Beauchet-Filleau et al., 2018). For instance, chlorella was found to improve the digestive function and milk yield of goats (Kholif et al., 2017). Amino acid profile is a key determinant of feed quality, and microalgae like chlorella and spirulina have profiles that resemble soybean, the leading source of feed protein (Amorim et al., 2021). Microalgae can also provide key minerals, thus avoiding imbalances that can hamper feed conversion and animal growth (Tibbetts et al., 2015).

Using microalgae as a feed supplement also provides CC mitigation opportunities in two distinct ways. Most simply, it offers scope to partially replace leading supplements like soy (Walsh et al., 2015; Lamminen et al., 2019) that have a large carbon footprint due to causing deforestation and transport emissions. By contrast, microalgae requires comparatively little land and could be locally sourced (see Section Is microalgae cultivation climate resilient?). Microalgae-based supplements may also help reduce enteric methane emissions from ruminants, since these emissions are associated with poor digestive function and lost feed energy. The potential for protein supplements to improve ruminant digestive function and mitigate enteric emissions is thought to be highest in the tropics (Knapp et al., 2014; Halmemies-Beauchet-Filleau et al., 2018).

Walsh et al. (2015) modeled possible impacts of wider use of microalgae as a livestock feed. They suggest this could boost the efficiency of livestock production and enable better use of land and water, thus supporting food security while creating scope to reduce deforestation and GHG emissions. They estimate microalgae feed could free up 40% of existing pastures and feedcrop land by 2100 while securing large GHG emissions reductions, and suggest this merits serious consideration as a CC mitigation option. They note however that realizing such outcomes would require addressing challenges like designing systems that are robust against contaminants and can recycle water across successive harvests. Palatability issues may also require attention, notably at higher concentrations of microalgae in feed (Van Emon et al., 2015).

Microalgae-based biofertilizers and biostimulants for crop support

World agriculture has depended heavily on chemical fertilizers to boost crop productivity and meet food needs over the past several decades, yet mounting evidence suggests these chemicals can undermine agricultural sustainability. Critically, excessive use of such products is not climate smart. It can lead to soil degradation (Guo et al., 2010) including depletion of soil organic matter (Odhiambo and Magandini, 2020), and hence aggravate the vulnerability of cropping to CC by reducing the water-holding capacity of soils. Chemical fertilizers also seem ill-suited to coping with CC, since under hot and/or dry conditions crop response can be marginal (Odhiambo and Magandini, 2020) or even deleterious (Bushong et al., 2016). They also contribute to GHG emissions via their status as fossil-fuel based products.

Biofertilizers and biostimulants are natural alternatives that can boost crop production while making it more sustainable and resilient to stresses (Garcia-Gonzalez and Sommerfeld, 2016; Van Oosten et al., 2017). They also offer scope to make crop production climate smart, though most authors do not explicitly make this link. While definitions of these terms vary between papers, both are substances of biological origin that can either take the form of extracted chemical compounds or inoculants of living microorganisms.

Biofertilizers contain key plant nutrients in forms that support plant growth. They can increase soil nutrient availability, thus fostering plant growth while also reducing reliance on chemical fertilizers (Ronga et al., 2019; Guo et al., 2020; BHU, 2022; Cordeiro M. R. C. et al., 2022).

Biostimulants are substances that promote plant growth when applied to plants or soil without being nutrient sources, soil improvers, or pesticides. They function by stimulating biological and chemical processes in plants and/or associated microbes like mycorrhizal fungi. This can facilitate nutrient uptake, raise yields, improve crop quality, and/or enhance crop tolerance to stresses like heat and salinity (Du Jardin, 2015; Ronga et al., 2019; Navarro-López et al., 2020).

Biofertilizers and biostimulants derived from microalgae are attracting growing attention from both researchers and farmers. This is reflected in spiking numbers of both academic papers and patents in recent years driven by factors like sustainability concerns and demand for organic food (Murata et al., 2021). At present, however, these products remain largely unexploited (Ronga et al., 2019).

Various studies have clearly demonstrated the potential efficacy of microalgae-based biofertilizers and biostimulants (Tables 4, 5), although factors like timing and dosage can be important (Vernieri et al., 2005).

Crop production can be threatened by abiotic stresses linked to CC like elevated temperatures, water scarcity and soil salinity (Biancardi et al., 2010; Ronga et al., 2018). An emerging literature on pertinent aspects of microalgae-based biofertilizers and biostimulants offers grounds for hope that these technologies might in time provide ways to build crop resilience to these stresses (Table 6).

Some microalgae can also function as soil amendments when applied to fields and may offer ways to control erosion and limit any yield losses from CC impacts like erratic rainfall. Kheirfam et al. (2017) examined the effect of using a microalgal inoculant on rainfall-induced soil erosion in Iran and found that soil losses decreased by 73–98% following treatment thanks to creating biofilms that formed larger more stable soil particles. Malam Issa et al. (2007) investigated the impact of microalgal inoculation on degraded soils in South Africa and found treated soils showed improved aggregate stability that increased gradually over time due to binding and gluing effects by microbes. Trejo et al. (2012) tested the potential for alginate beads to restore eroded, infertile soil in an arid part of Mexico and found they sharply increased fertility measures like soil carbon and growth of sorghum crops.

Microalgae as biochar feedstocks

Another way microalgae could potentially support crop production is via using algal biomass to make biochar, or charred biomass. Biochar is formed by heating organic matter like wheat stover, sawdust or microalgae over time in the absence of oxygen (i.e., pyrolysis). The resulting product can serve as a soil amendment, as advocated by entities like the

TABLE 4 Efficacy of microalgae-based biofertilizers on crops.

Crops	Study findings
Maize, wheat	Key parameters like germination rate and plant height roughly doubled (Uysal et al., 2015)
Organic onions	Enhanced plant growth; delivered yield increases of 28–40% (Cordeiro E. C. et al., 2022; Cordeiro M. R. C. et al., 2022)
Wheat	Boosted plant dry weight by 7–33% and grain weight by 6–8%; enhanced mineral content (Renuka et al., 2016)
Leafy vegetables	Strongly enhanced growth with effects comparable to chemical fertilizer (Wuang et al., 2016)
Corn	One microalgae biofertilizer significantly increased plant growth while two others decreased it (Ekinci et al., 2019)
Rice	Significantly raised yields but was most effective when used together with chemical fertilizers (Jha and Prasad, 2006)

TABLE 5 Efficacy of microalgae-based biostimulants on crops.

Crops	Study findings
Organic tomatoes	Doubled key parameters like fruits per plant and total soluble sugars while also improving factors like plant height (Suchithra et al., 2022)
Watercress	Boosted watercress germination by 40% and plant hormonal activity by 60–187%, with stimulant effects strongest at low concentrations (Navarro-López et al., 2020)
Seed spice crops	Increased root and shoot length by 30–50% and gave a two- to three-fold increase in the "vigor index" of plants, which combines growth and germination rates (Kumar et al., 2013)
Wheat	Two microalgae strains were found to boost germination by 26–147%, but stimulant effects were strongest at low concentrations, notably 0.2 g/L (Viegas et al., 2021a)
Watercress, wheat	Two microalgae biostimulants boosted growth of watercress (77–238%) and wheat (70–98%) (Viegas et al., 2021b)

TABLE 6 Examples of studies that explored aspects of these technologies pertinent to climate resilience.

Threat	Study findings
Drought, heat, salinity	Van Oosten et al. (2017) reviewed evidence on whether biostimulants could help crops tolerate abiotic stresses and found numerous studies suggesting they can help crops cope with drought, heat, and salinity, but only a few of the biostimulants considered were based on microalgae.
Heat, drought	Santini et al. (2021) tested spirulina-based biostimulants on grapevines facing heat stress and drought and observed greater tolerance of such conditions resulting in higher berry weight (+11%).
Drought	Martini et al. (2021) tested chlorella-based biostimulants on maize plants and observed greater root development and accumulation of microelements in plant tissue, resulting in enhanced tolerance to nitrogen deficiency and improved resistance to drought stress.
Water stress	Oancea et al. (2013) tested nannochloris-based biostimulants on well-watered and water-stressed tomato plants. On well-watered plants biostimulants more than doubled root length, leaf number and leaf area, while on water-stressed plants they alleviated the adverse effects of water stress on root development and strongly mitigated adverse effects on plant height.
Water stress	Mancuso et al. (2006) tested a microalgae extract as a biostimulant on grape plants and found it increased leaf water potential and stomatal conductance under drought stress.
Salinity	Abd El-Baky et al. (2010) tested spirulina and chlorella extracts on wheat plants irrigated with seawater and found they helped the plants cope with salinity while also sharply enhancing the nutritional profile of wheat grains, including their protein content and antioxidant capacity.
Salinity	Guzmán-Murillo et al. (2013) tested two microalgal extracts on bell pepper seeds facing salt stress and observed longer roots and lower stress effects, resulting in substantially higher germination rates.

International Biochar Initiative (2022). This can improve the availability of soil nutrients, enhance soil water-holding capacity, and support beneficial soil microbes, with impacts greatest on degraded soils (Roberts et al., 2010; Whitman et al., 2010; Lehmann and Joseph, 2015). Such changes can restore degraded soils and hence support crop production in areas where land degradation is prevalent. They can also build the climate resilience of production by helping crops cope with CC impacts like erratic rainfall and extreme weather events, though none of the papers reviewed made this link.

A key feature of biochar is its stability. Notably, when used as a soil amendment its carbon components are highly recalcitrant, with estimated residence times in soil of hundreds to thousands of years (Spokas, 2010; Lehmann and Joseph, 2015). Biochar use was a traditional soil management practice in some cultures, and some treated fields have remained distinct over time (Lehmann and Joseph, 2015). For instance, *terra preta* soils in Brazil treated by the Amerindians many centuries ago were found to contain up to 9% carbon compared with 0.5% on neighboring lands, while their productivity was estimated to be twice as high (Marris, 2006). This stability enables biochar to make lasting changes to soils, including fixing atmospheric carbon in soils and thus potentially offering options for CC mitigation, though net GHG flux effects will also depend on factors like the feedstock and heat source used to produce biochar (Lehmann and Joseph, 2015).

Some early studies have investigated biochar made from microalgae and its potential as a soil amendment. Wang et al. (2013) studied the organic elements and minerals in biochar made from chlorella and suggested it had good prospects as a soil amendment. Gong et al. (2014) examined biochar made from two types of microalgae and found they had a higher content of nitrogen and various minerals compared to those made from lignocellulosic feedstocks like sawdust or rice husk. Chang et al. (2015) conducted chemical analysis of biochar derived from chlorella and suggested it could be used as a mineral-rich soil amendment. One caveat however is that if this chlorella contains heavy metals then these could be incorporated into biochar and released into soil. Minimizing or removing any such contaminants is thus a priority where microalgae are to be used as biochar feedstock.

Other studies have investigated the potential of microalgae-based biochar as both a soil amendment and CC mitigation option. Yu et al. (2018) found that biochar derived from chlorella was suitable for use on agricultural soils while also contributing to CC mitigation thanks to its chemical composition. Zhao et al. (2013) compared different biochar feedstocks including chlorella and found that biochar properties key to crop support and CC mitigation potential (e.g., total carbon, carbon sequestration capacity) were largely a function of feedstock type, and that chlorella performed well by such measures. Chen et al. (2021) examined biochar derived from chlorella compared to those derived from soybean straw and sawdust and found that it had higher nitrogen content but lower carbon content, though all three showed potential to both improve soils and mitigate CC.

Discussion

CC poses an existential threat to agriculture and food supplies via impacts like erratic rainfall and more frequent or severe extreme weather events. Parts of the Global South may be at particular risk from climatic shocks, notably areas where agriculture and herding are already marginal due to factors like poor soil conditions and limited access to inputs like irrigation, improved seeds, or vaccines.

Conventional agricultural production is highly vulnerable to CC especially when coupled with environmental degradation. For instance, maize or sorghum may struggle due to poor or erratic rains, while cattle or goats may struggle where pastures or water sources become depleted. Inputs like irrigation, fertilizers, and improved seeds can overcome such stresses to a point but may see diminishing returns over time due to factors like salinization and depletion of soil organic matter or aquifers (Wise, 2020). There is thus an urgent need for innovative options to ensure the climate resilience of agriculture and the security of food supplies.

Future foods, agri-food uses of microalgae, and building climate resilience

Future foods (FFs) like microalgae, insects and mycoprotein (i.e., fungus) are an emerging class of foods that show promise as nutritious and sustainable dietary options. These foods can also complement or substitute for conventional plant-sourced foods (PSFs) and animal-sourced foods (ASFs) in various ways (Tzachor et al., 2021).

The defining characteristic of FFs is that they are typically produced within controlled systems that are often also enclosed. For instance, microalgae is cultivated in man-made ponds or enclosed bioreactors while insects are grown in stackable, multicompartment nurseries. Such farming systems enable greater control over the physical, chemical, and biological conditions of production, which can boost performance and potentially deliver elevated production per unit time and area. These farms can also sharply reduce exposure to biotic and abiotic stresses. Critically, such systems may enable farmers to sidestep threats like water scarcity and pest attacks that might otherwise jeopardize farm production (Tzachor et al., 2021).

Given their profile, FFs like microalgae hold promise as options to deliver vigorous and sustainable production despite stresses including CC, in contrast to farms producing PSFs and/or ASFs. Figure 2 considers how well PSF, ASF, and FF farming systems cope with different stresses using maize, cattle, and spirulina as case studies. While this typology shows tendencies for these different farm types, farm performance given stresses clearly also depends on local factors like whether or not climate smart practices are employed.

The present review builds on this foundation by exploring the linkages between one group of future foods and one abiotic stress, namely microalgae and CC. This includes examining how different agri-food uses of microalgae might offer options to build the climate resilience of both farmers and food supplies.

Via their agri-food applications, microalgae offer several distinct avenues for building climate resilience. Figure 3 shows the ways they can boost the climate resilience of wider food supplies, namely fostering robust, sustained production of this FF despite CC while also enhancing the resilience of PSF and ASF production. Figure 4 shows how they can provide climate resilient livelihood pathways for farming communities that are vulnerable to CC shocks, such as small-scale farmers in Africa.

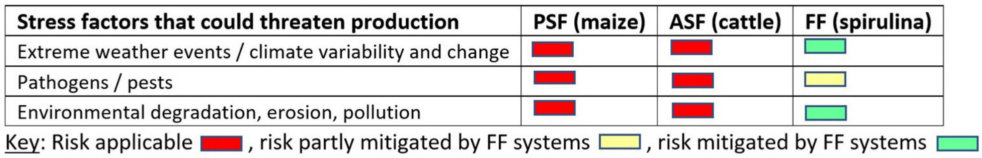

FIGURE 2
How well PSF, ASF, and FF farming systems cope with major stresses (adapted from Tzachor et al., 2021).

Figure 4 includes an additional resilience factor besides the effects of microalgae on food production, namely creating scope to harness climate finance flows. Climate finance is defined as "all financial flows whose expected effect is to reduce net GHG emissions and/or to enhance resilience to the impacts of climate variability and the projected climate change" (IPCC, 2014). The prerequisite for any such flows would be for microalgae investments to be recognized as viable means to deliver on CC objectives, which is not presently the case. If this were addressed, it would set the stage for climate finance to be channeled to microalgae initiatives via NDC plans or offset projects (see Section Agri-food applications of microalgae and CC mitigation below).

Climate resilient development pathways are defined as trajectories that successfully integrate sustainability, CC adaptation and CC mitigation considerations to deliver human wellbeing and planetary health. Climate resilient development has emerged as a guiding principle for climate policy and action (IPCC, 2022e), as reflected in a growing literature on pathways (e.g., Quandt et al., 2017; Ellis and Tschakert, 2019).

Whether or not vulnerable farmers can access climate resilient livelihood pathways could have profound consequences over time both locally and more widely. Figure 5 illustrates how the effects of CC shocks and related stresses can differ depending on whether or not farmers can access viable technological options to build climate resilience. Without such options, farmers might resort to desperate measures like depleting key resource stocks (Adger et al., 2014; IEP, 2020; Siedenburg, 2021) that could see them fall into a "vicious circle" of rising climate vulnerability and deepening poverty. Conversely, if they could access viable technologies, this might enable them to instead reach a "virtuous circle" of climate resilience and food security (Pimbert, 2012; Hendrix and Brinkman, 2013).

Agri-food applications of microalgae and CC mitigation

AFOLU measures like agroforestry or livestock management are seen as offering scope for substantial CC mitigation at relatively low cost. The IPCC estimates that AFOLU could provide 20–30% of needed CC mitigation to remain within a 1.5–2°C emissions trajectory to 2050, and that 30–50% of this could be achieved at a carbon price of $20/ton CO2 equivalent (tCO2e) or less. AFOLU measures are also well-positioned to deliver co-benefits that foster climate resilience like boosting soil productivity, water availability, and food security (IPCC, 2022c).

Despite such promise, implementation of AFOLU measures remains limited due to barriers such as insufficient financial and policy support. The IPCC has suggested that national investment plans under NDCs are urgently needed to accelerate AFOLU deployment, coupled with policy levers like payments for ecosystem services and fostering engagement from the private sector and charities (IPCC, 2022c).

The linkages of microalgae to GHG emissions and the goal of CC mitigation are complex. Microalgae absorb CO2 and transform it into microalgal biomass and hence could potentially help mitigate CC, especially since some studies suggest they can fix atmospheric carbon significantly more efficiently than terrestrial plants (Pires et al., 2014). Alternatively, however, microalgae could have ambiguous or even negative impacts on GHG dynamics.

One key question is the sourcing of microalgae production inputs like light, heat, water, nutrients, and CO2. Notably, utilizing fossil-based energy inputs undermines CC mitigation potential, while relying on renewable energy or waste streams enhances it (Fonteinis et al., 2018; Khan et al., 2019).

Another key question is how microalgal biomass is used. Several agri-food uses of microalgae offer possible pathways to deliver CC mitigation (Table 7). This includes using microalgae-based feeds to reduce deforestation pressures, replacing agro-chemical inputs with biofertilizers and biopesticides, and producing biochar to sequester CO2 in a stable form.

Carbon offsets are a major source of climate finance that can foster delivery of CC mitigation actions by entities such as businesses and charities (Ecosystem Marketplace, 2021). They involve buyers paying those who deliver verifiable CC mitigation outcomes to carbon markets via approved activities (Lee, 2017). If any agri-food applications of microalgae were formally recognized as offset options, this could provide a mechanism for those delivering these applications to earn income from these markets.

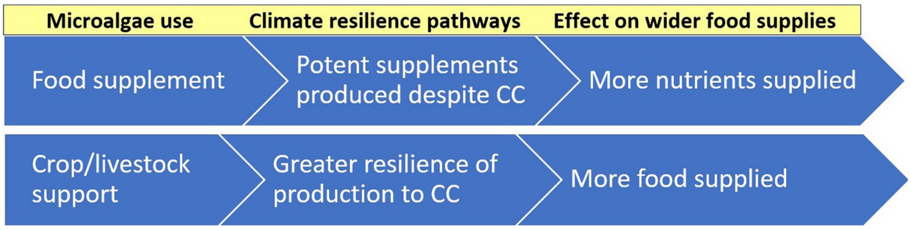

FIGURE 3
Agri-food uses of microalgae and pathways to enhanced climate resilience of food supplies.

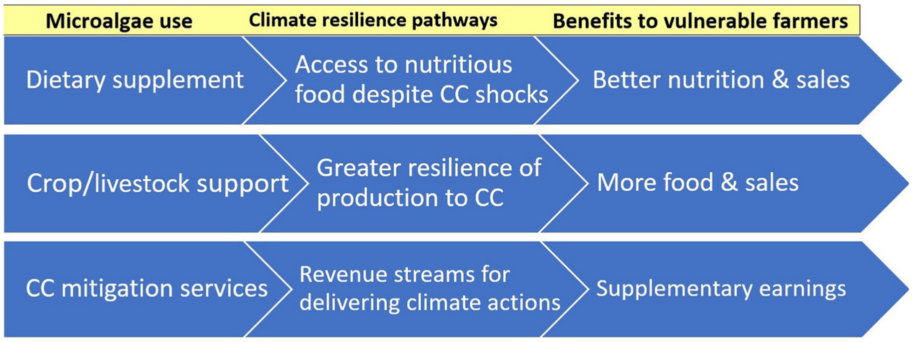

FIGURE 4
Agri-food uses of microalgae and pathways to enhanced climate resilience of vulnerable farmers.

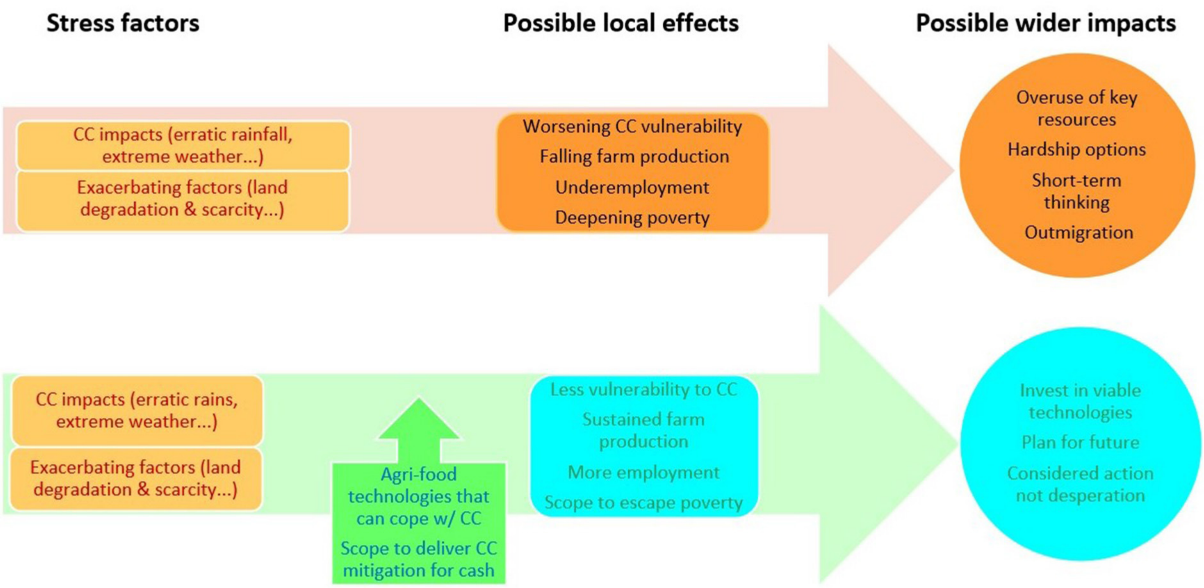

FIGURE 5
Differing effects of CC on vulnerable small-scale farmers depending on whether they can access viable technologies.

While the theory that offsetting is mutually beneficial has sometimes proven problematic in practice (Watt, 2021), efforts to foster sound offsetting practice continue (Allen et al., 2020).

Notwithstanding such competing perspectives, one critical reality is that the agri-food uses of microalgae flagged as possible CC mitigation options could, it seems, also foster climate resilience based on the available evidence (Table 7). It follows that any offset payments to fund such options may foster both outcomes simultaneously. This would fit with the IPCC's suggestion that integrated measures which contribute to both mitigation and adaptation have a greater likelihood of being successful (IPCC, 2022c).

One factor that fundamentally affects any discussions about CC mitigation options is the carbon price. A higher carbon price could augment the profitability of activities or products that qualify as CC mitigation options, thus strengthening the incentives for economic actors to deliver them. Until 2018 the price of the leading carbon market was typically under €10/ton, but since early 2022 it has been approximately €80/ton, so prices have risen sharply (Trading Economics, 2022).

One risk is that efforts to explore such CC mitigation prospects may face accusations of "greenwashing" that could have a chilling effect. For instance, a leading environmentalist recently tweeted "Every sector needs to be decarbonised" and "offsetting… solves nothing" (Monbiot, 2021), while a leading climate scientist tweeted, "Normalize ridiculing carbon offsets and net zero" (Kalnus, 2021). Such critics support their arguments by citing troubling examples of immoral practice, like Shell telling its customers that thanks to its global portfolio of offset projects, "you don't even have to change the way you work" (Monbiot, 2021).

Regrettably, such blanket condemnations neglect economic realities, notably the fact that financial considerations can be key determinants of action. Poorer populations like small-scale farmers in the Global South may be especially unlikely to take innovative actions without clear incentives, given their often tenuous circumstances (Siedenburg et al., 2015). Such communities often address shocks or stresses via short-term coping responses rather than transformative adaptations, but strategic financial investments can help overcome barriers to more proactive responses (IPCC, 2022d). Given the scale of the climate challenge, it is to be hoped that such critics move toward being more constructive about offsetting, ideally by deploying their influence to improve practice and minimize abuses.

While agri-food applications of microalgae may offer potential CC mitigation opportunities, realizing this potential will depend on essential building blocks being in place. This includes further developing the relevant technologies and institutional factors like elaborating carbon market methodologies to enable selected microalgae technologies to qualify for mitigation finance.

Summarizing findings on microalgae and climate action

Table 7 summarizes this paper's analysis, highlighting how the five agri-food uses of microalgae examined might serve as the basis for climate action, including both adaptation to and mitigation of CC. In cases where microalgae are used for agricultural support, it should be noted this can be compatible with organic farming and the price premiums it offers (Colla and Rouphael, 2020). This summary assumes energy needs are met by renewable power given its plummeting costs, thus minimizing GHG emissions from energy. One factor not included in the table is how climate finance could potentially be provided to support initiatives on any of these technologies, and how such cashflows could represent an additional aspect of climate resilience for farming communities.

Potential risks and obstacles

Of the many microalgae species relatively few are well-known, yet several (e.g., Arthrospira, Chlorella, Dunaliella) have been designated as generally safe for human consumption by the regulatory authorities of key jurisdictions like the European Union (Niccolai et al., 2019) and United States (Chacón-Lee and González-Mariño, 2010).

Consumption of any food is not without risk, however, so potential harm to consumers must be considered. One possible concern is allergic reactions to eating microalgae. Another is contamination of microalgae with biotic pathogens like microcystins or abiotic toxins like heavy metals (Inthorn et al., 2002; Becker, 2013; Wells et al., 2017). Some early studies have sought to examine these linkages, but further research is needed. Al-Dhabi (2013) examined 25 commercial spirulina supplements and found that heavy metal levels were well below the allowable daily intake in all cases. Roy-Lachapelle et al. (2017) examined 18 microalgae supplements and found that four contained microcystins at levels exceeding tolerable daily intake.

Risk mitigation measures are clearly needed for microalgae destined for use as food or feed (Amorim et al., 2021). Microalgae cultivated in open ponds are more vulnerable to contamination (Heussner et al., 2012), while enclosed cultivation systems can reduce contamination risk but can also be capital-intensive (Linder, 2019). Hybrid options like open ponds within greenhouses offer scope to balance these considerations by reducing contamination risk cost-effectively

TABLE 7 Possible ways agri-food applications of microalgae could serve as climate actions.

Application	CC adaptation/building climate resilience	CC mitigation
Food	• By creating scope for ongoing production of a valuable crop despite CC, microalgae reduces risk that farmers experience hunger or desperation • Microalgae could be consumed to boost health and vigor or sold to create an income stream	• Vulnerable farmers have less need for hardship behaviors that can deplete carbon pools (e.g., selling fuelwood or charcoal), since microalgae offers a secure source of food/income
Feed	• Better nutrition despite CC helps ensure animal strength, minimizing CC-related mortalities • Better nutrition enables livestock to maintain production of milk, eggs, offspring despite CC	• Reduced dependency on feeds like soy that cause deforestation and transport emissions • Potential to reduce enteric methane emissions from ruminants
Biofertilizer and biostimulant	• Ample crop nutrients and stimulated biology raise crop productivity and boost resilience to CC-related stresses like heat, drought, and salinity	• Reduced use of petroleum-based chemical fertilizers • Using bioproducts can gradually enhance soil carbon
Biochar	• Stable soil carbon boosts fertility and water-holding capacity of soils, making cropping more resilient to climatic shocks	• Biochar fixes CO2 in a stable form suitable for use as a soil amendment

(Lu et al., 2011). Another option that has shown promise is varying the temperature or salinity of the culture medium in ways that microalgae can tolerate but other species may not (Wang et al., 2016).

Despite growing use of microalgae as foods, consumer acceptance remains an issue, as does the affordability of microalgal biomass. These issues are likely to be key determinants of future demand for edible microalgae (Linder, 2019) and hence merit greater attention. One possible way to enhance consumer acceptance is raising awareness of the health and environmental benefits of microalgae (Linder, 2019), but early efforts to foster microalgae consumption suggest that information provision on its own may be ineffective due to strong cultural associations with food (AIM, 2016).

Research and policy priorities

While the literature reviewed suggests clear potential for the agri-food technologies examined to serve as the basis for climate actions, the evidence base remains thin. Research priorities include:

- Conducting further investigations of these agri-food technologies to explore and verify their suitability for building climate resilience and mitigating CC. This should include studies under real world conditions, since such studies are critical for assessing the viability of technologies.
- Identifying ways to lower the costs of microalgae production while maintaining quality standards, including developing improved "appropriate technology" production systems.
- Identifying effective, accessible strategies to minimize contamination risks to microalgae production.
- Trialing agri-food applications of microalgae with small-scale farmers in the Global South to assess their efficacy in a context that is a focus of global concerns about food insecurity and vulnerability to CC.
- Quantifying tons of CO2 equivalent that could be delivered by microalgae technologies identified as promising CC mitigation measures, coupled with developing improved and affordable measurement, reporting and verification measures.
- Assessing the scope for business engagement with deploying agri-food applications of microalgae as climate actions, given claims like "businesses are now in hyperdrive when it comes to climate (Financial Times, 2022)."
- Exploring why there is not greater interest in microalgae and their agri-food uses from governments and international agencies, given their technological promise.
- Examining why farmers and consumers do not show greater interest in microalgae as a crop and food given their promise, while also identifying and investigating any barriers to demand.
- Assessing whether other microalgae species besides those emphasized by research and commercial applications to date show promise as agri-food technologies given CC.

Policy measures would also be needed to elaborate and harness the technological potential suggested by this review. Policy priorities include (i) funding studies to address research priorities; (ii) incorporating these technological options into policy documents such as NDC plans and climate finance schemes; and (iii) developing carbon market methodologies for the most promising CC mitigation options.

Conclusions

Across the globe, CC poses a serious and growing risk to agricultural production and food security, especially for vulnerable populations like small-scale farmers in the Global South. Effective response actions are needed, notably ones that offer scope to secure continued agricultural production and ample, nutritious food despite CC. The academic evidence reviewed suggests that using microalgae as a food, feed or crop support technology shows promise in this regard for both vulnerable farmers and wider society, while also potentially offering CC mitigation options. Characteristics of microalgae that make them well-suited to facing the looming CC challenge include (i) growing fast and not needing arable land or regular rainfall, (ii) being highly nutritious as a food or feed, and (iii) capacity to support "climate smart" crop and livestock production. While the promise of these agri-food technologies is clear, further research is needed to explore and substantiate their potential, and to examine issues like risks and barriers to uptake. In the meantime, such technologies merit greater attention from practitioners like farmers and governments as promising and timely technologies.

Author contributions

JS conducted the literature search, analysis, and wrote the paper.

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Conflict of interest

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

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Corrigendum: Could microalgae offer promising options for climate action via their agri-food applications?

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In the published article, there was an error in Table 4 as published. In row 2 of this table on 'organic onions', the citation was displayed as "Cordeiro E. C. et al., 2022; Cordeiro M. R. C. et al., 2022". The correct citation is "Cordeiro, E. C. et al., 2022". The corrected Table 4 appears below.

In the published article, there was an error in Table 5 as published. The final row of this table on 'watercress, wheat' included incorrect percentages, though these did not change the pertinence of the source cited. This text read "Two microalgae biostimulants boosted growth of watercress (77-238%) and wheat (70-98%)". It should read "Two microalgae biostimulants boosted germination of watercress by 48–175% and of wheat by 84–98%." The corrected Table 5 appears below.

In the published article, there was an error in Table 6 as published. In row 4 concerning 'water stress', the impact of biostimulants on well-watered plants was mistakenly overstated. The relevant text reads "On well-watered plants biostimulants more than doubled root length, leaf number and leaf area…". It should read "On well-watered plants biostimulants significantly boosted root length, leaf number and leaf area…". The corrected Table 6 appears below.

The authors apologize for these errors and state that they do not change the scientific conclusions of the article in any way.

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TABLE 4 Efficacy of microalgae-based biofertilizers on crops.

Crops	Study findings
Maize, wheat	Key parameters like germination rate and plant height roughly doubled (Uysal et al., 2015)
Organic onions	Enhanced plant growth and delivered yield increases of 28–40% (Cordeiro E. C. et al., 2022)
Wheat	Boosted plant dry weight by 7–33% and grain weight by 6–8%; enhanced mineral content (Renuka et al., 2016)
Leafy vegetables	Strongly enhanced growth with effects comparable to chemical fertilizer (Wuang et al., 2016)
Corn	One microalgae biofertiliser significantly increased plant growth while two others decreased it (Ekinci et al., 2019)
Rice	Significantly raised yields but was most effective when used together with chemical fertilisers (Jha and Prasad, 2006)

TABLE 5 Efficacy of microalgae-based biostimulants on crops.

Crops	Study findings
Organic tomatoes	Doubled key parameters like fruits per plant and total soluble sugars while also improving factors like plant height (Suchithra et al., 2022)
Watercress	Boosted watercress germination by 40% and plant hormonal activity by 60–187%, with stimulant effects strongest at low concentrations (Navarro-López et al., 2020)
Seed spice crops	Increased root and shoot length by 30–50% and gave a two- to three-fold increase in the "vigour index" of plants, which combines growth and germination rates (Kumar et al., 2013)
Wheat	Two microalgae strains were found to boost germination by 30 to 147%, but stimulant effects were strongest at low concentrations, notably 0.2 g/L (Viegas et al., 2021a)
Watercress, wheat	Two microalgae biostimulants boosted germination of watercress by 48–175% and of wheat by 84–98% (Viegas et al., 2021b)

TABLE 6 Examples of studies that explored aspects of these technologies pertinent to climate resilience.

Threat	Study findings
Drought, heat, salinity	Van Oosten et al. (2017) reviewed evidence on whether biostimulants could help crops tolerate abiotic stresses and found numerous studies suggesting they can help crops cope with drought, heat and salinity, but only a few of the biostimulants considered were based on microalgae.
Heat, drought	Santini et al. (2021) tested spirulina-based biostimulants on grapevines facing heat stress and drought and observed greater tolerance of such conditions resulting in higher berry weight (+11%)
Drought	Martini et al. (2021) tested chlorella-based biostimulants on maize plants and observed greater root development and accumulation of microelements in plant tissue, resulting in enhanced tolerance to nitrogen deficiency and improved resistance to drought stress.
Water stress	Oancea et al. (2013) tested nannochloris-based biostimulants on well-watered and water-stressed tomato plants. On well-watered plants biostimulants significantly boosted root length, leaf number and leaf area, while on water-stressed plants they alleviated the adverse effects of water stress on root development and strongly mitigated adverse effects on plant height.
Water stress	Mancuso et al. (2006) tested a microalgae extract as a biostimulant on grape plants and found it increased leaf water potential and stomatal conductance under drought stress.
Salinity	Abd El-Baky et al. (2010) tested spirulina and chlorella extracts on wheat plants irrigated with seawater and found they helped the plants cope with salinity while also sharply enhancing the nutritional profile of wheat grains, including their protein content and antioxidant capacity.
Salinity	Guzmán-Murillo et al. (2013) tested two microalgal extracts on bell pepper seeds facing salt stress and observed longer roots and lower stress effects, resulting in substantially higher germination rates.

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Climate resilient agriculture and enhancing food production: Field experience from Agusan del Norte, Caraga Region, Philippines

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This paper describes the assessment of climate risks, the vulnerability of farmlands, and the adaptive farming practices to climate change with the use of GIS, field observations, stakeholder consultation and interviews and case documentation. GIS-based climate risk vulnerability assessment maps were generated to pinpoint the areas with the major climate hazards in Agusan del Norte. The vulnerability of the farmlands, and the adaptive capacity of the farms were assessed with index scoring. Also, adaptation to climate change based on the most problematic hazard (flooding) was observed on the two groups of farmers (with and without climate resilient agriculture (CRA)/cropping system adjustments) for cost and benefit comparison. The results show flooding and drought as the significant hazards in Agusan del Norte (Caraga Region) and high vulnerability to these hazards due to low coping mechanisms for most farms. Low adaptive capacity was also observed among these farms. Case-based observations on adaptation in Jabonga, Agusan del Norte revealed that well-timed adjustments to the usual cropping system can increase farm income despite of the flood and inundation for 2–3 months. This study recommends for harmonized measures toward advocating strengthened adaptive capacity for agriculture across Agusan del Norte. Further climate R&D and increasing policy support on climate financing and CRA options are highly encouraged for the agricultural stakeholders to take action. For hard-pressed farmers with constrained access to improved varieties and technologies, timing is potentially essential to circumvent damages from climate change to gain economic and psychosocial benefits with well-timed adaptation measures.

KEYWORDS

climate change, climate-resilient agriculture, mitigation, vulnerability mapping, adaptive capacity, climate risk

Introduction

Strategies to reduce the impacts of climate change through mitigation and adaptation are necessary to improve the resilience of the agriculture-based communities (Porter et al., 2014 as cited by Escarcha et al., 2018; Aryal et al., 2020), particularly in the various regions in the Philippines. Developing countries with tropical climates like the Philippines are potentially sensitive and vulnerable to these impacts for a lot of reasons (Escarcha et al., 2018). In Mindanao, agricultural development in the north-eastern regions have been continually exposed to different climate hazards such as typhoon, drought, erosion, and pest and diseases brought about by the changing climate, inappropriate cultivation, and land-use practices. These are collectively called human-driven or anthropogenic climate change that can cause great damage to farming and agriculture and exacerbate poverty among the disadvantaged rural population (Barbier and Hochard, 2018; Stuecker et al., 2018). Barbier and Hochard (2018) pointed out climate-induced events with immediate impacts such as floods, droughts and storm surges, and climatic changes with gradual impacts such as temperature and rainfall changes, sea level rise and intrusion as well as soil erosion as damaging to the ill-equipped agriculture and farming population. They have identified the people living in the "less favored agricultural areas (LFAAs)" as extremely vulnerable to climate change events due to management difficulties caused by poor location and resource quality endowments. In 2011–2020, the north-eastern Mindanao region with sporadic LFAAs was subjected to such conditions with typhoons causing tremendous agricultural damage. These experiences of north-eastern Mindanao affirm the expanding vulnerabilities of the agriculture-dependent economy and the farming communities where damages consequently intensify the poverty situation.

The recognition that climate change can negatively affect agricultural production has led governments to build resilience into agricultural systems. In the EU, adaptation is an objective for agricultural units in the region to work out under the Common Agricultural Policy (CAP) 2021–2027 with several portfolios of technologies and approaches to institute farm/agricultural resilience (Tigkas et al., 2020). For the same reason, public investments have been used in the Philippines to strengthen the staple food baskets, particularly the rice sector with irrigation facilities (Perez et al., 2018). On the other hand, cropping systems through crop diversification can potentially improve resilience in two ways: by stimulating biodiversity that can suppress pest outbreaks and dampen pathogen transmission, and by protecting crop production from the effects of climate variability and extreme events (Lin, 2011) with relevant technologies and approaches. For India, crop diversification works as an effective option to crop enterprise resilience, particularly in areas constrained by limited rainfall and high temperature (Birthal and Hazrana, 2019). However, crop diversification as an adaptation strategy is challenged by the incentives to produce with a select few crops and the belief that monocultures are more productive than diversified systems. Such incentives and beliefs can deter the promotion and adoption of crop diversification to reduce climate change impacts.

Meanwhile, adaptation to climatic changes has been studied for behavioral underpinnings as a basis for interventions by the government and other organizations. In the Philippines, Acosta-Michalik and Espaldon (2008) used an agent-based framework with a behavioral component for village farmers in a municipality. In their study, the framework's simulations had provided insights that production support can reduce future vulnerability if matched with appropriate market support. Acosta-Michalik and Espaldon (2008) also reported that the lack of money and information are the most important reasons why available technical adaptation measures in the community fail. However, a participatory approach to managing climate change risks and adaptation requires substantial stakeholders' learning (Grimberg et al., 2018) as well as learning the location requirements of community-based adaptation strategies (Makate, 2020). Downscaling vulnerability and risk assessment to the community and farm level are challenged with these (Tiongco, 2016). The role of forward-looking learning as a critical element for adaptation and resilience in the context of climate change is still being studied. Tschakert et al. (2014) present two linked methodological tools as an assessment of change drivers and participatory scenario building used in a climate change adaptation project in Ghana and Tanzania. Their results suggest that joint exploration, diverse storylines, and deliberation help to expand community-based adaptation lists and strike a balance between hopelessness and a tendency to idealize potential future realities.

In the Philippines, the successful implementation of the government-initiated program on climate change adaptation and mitigation at the regional level requires the active collaboration and support of key research and development institutions within the region (Grimberg et al., 2018; Makate, 2020). Caraga Region is a flood-prone area, thus, flooding is regarded as the major disaster that significantly affects the socio-economic conditions of the region. The guidelines set by the government to allocate funds for disaster risk reduction and management due to climate change is a huge opportunity for financing climate resilient agriculture (CRA) initiatives. However, rational investment planning is required to capitalize on the funds available for this purpose. Geospatial assessment of climate risks, documenting and analyzing climate-resilient agricultural practices and initiatives are important inputs in developing climate change adaptation or mitigation strategies in agriculture. This research developed maps of climate risks for local government units as the basis for CRA investment planning and the capacitation of the stakeholders for enhanced awareness of climate adaptation planning.

Methodology

Research site

The study was done in the province of Agusan del Norte in Caraga Region, Philippines. Caraga Region is in the northeastern part of Mindanao, Philippines with a land area of 18,847 sq.km (National Nutrition Council, 2021). It has five provinces, namely: Agusan del Norte, Agusan del Sur, Surigao del Norte, Surigao del Sur and the Dinagat Island. Aside from being a food and feed basket, the region is widely known as the mining destination and the timber corridor of the Philippines (Varela et al., 2021; Balanay et al., 2022). At present, Caraga Region has a total of 30 registered mining companies (MGB-13, 2020). It provided livelihood to people in the Province of Agusan del Norte and nearby provinces that increased the people's adaptability to climate change. Caraga Region is also responsible for the 65% timber supply across the country, which provides economic benefits to tree farmers and workers in the wood-based industry (Balanay et al., 2022). However, the region is reported to be among the most vulnerable areas in the country due to its location in the Pacific seaboard which is usually hit by typhoons. On average, 20 typhoons hit the Philippines every year.

In this study, climate mapping was piloted in the province of Agusan del Norte due to the interest of finding solutions to surmount the seemingly annual flooding incidence among the agricultural producers. Flood devastation in the key agricultural areas in Agusan del Norte is quite agonizing among the affected farmers with their inability to produce for income during the flood season of 2–3 months. Furthermore, climate maps were prepared for the major commodities such as rice, banana, and corn for Agusan del Norte. In the identification of changes in production practices to be recommended, the observation was focused on the corn producers who were found to be halted in agricultural production during the flood season due to inundation. These farmers were settlers in the municipality of Jabonga, Agusan del Norte. Jabonga has been experiencing massive flooding or inundation of at least a meter high every rainy season for at least 2 weeks.

Geospatial assessment of climate risks

Geo-referenced data on vulnerability to climate risks of the region's agriculture and fisheries sector were collected and organized. These datasets were formed from both primary and secondary sources. The primary data were obtained through interviews and focus group discussions. The component drivers of climate vulnerability such as sensitivity, exposure, and adaptive capacity, were assessed and evaluated using the composite index method to determine the risk and vulnerability levels within the study area. The sensitivity component analysis assumed a high emission scenario by the year 2050. The exposure component was the climate and hydro-meteorological related hazards that normally occur in the province, and adaptive capacity was the up-to-date secondary data from the respective local government units of Agusan del Norte.

The crop sensitivity under climate change employed a species distribution modeling through the Maximum Entropy (MaxEnt). This model underwent a two-step process; the first step was to evaluate the baseline crop suitability using the assumption that a species will most likely exist at a specific site if the environmental conditions are roughly similar to those observed. If the environmental condition where the species is detected in the baseline condition, the second step is to predict the location of the crop species on a particular time slice. The baseline and the future conditions were determined using the WorldClim dataset. Bioclimatic variables were created by processing the monthly rainfall and temperature data to produce more biologically meaningful climate variables (Hijmans et al., 2005). According to O'Donnell and Ignizio (2012), the bioclimatic variables are important parameters for understanding how different species react to climate change. The crop sensitivity index was determined by the difference between the baseline and future suitability to the changing climate conditions. An index ranging from 0.25 to 1.0 indicates a loss in suitability, while the negative direction (−0.25 to −1.0) indicates a gain in suitability, as suggested by Palao et al. (2017) as shown in Table 1.

The extent of exposure under pressure from the climate and hydro-meteorological risk was estimated using the combined georeferenced natural hazards such as tropical cyclone, flooding, landslide, storm surge, erosion, and sea-level rise. These hazards were validated during the consultation with the local government unit partners within the study area. Hazards weight

TABLE 1 Sensitivity index based on percent change in crop suitability from baseline to future condition.

Percent change in suitability (Range in %)	Index	Description
≤-50 (Very high loss)	1.0	Loss
>-50 ≤ −25 (High loss)	0.5	
>-25 ≤ −5 (Moderate loss)	0.25	
>-5 ≤ 5 (No change)	0	No Change
>5 ≤ 25 (Moderate gain)	−0.25	Gain
>25 ≤ 50 (High gain)	−0.5	
>50 (Very high gain)	−1.0	

were identified through focus group discussions participated by the experts from academe, national government agencies, and private stakeholders. The experts were asked to rate the risk of hazard based on the qualitative assessment using the following criteria: (a) Probability of occurrence; (b) Impact on local household income; (c) Impact on key natural resources to sustain productivity (refers to how key resources such as water quality and quantity, soil fertility, and biodiversity are affected); (d) Impact on food security of the country; and (e) Impact on the national economy. Experts were given a scale of 1–5, with 1 being low risk and 5 being a high probability of impact. Table 2 shows the percentage weight distribution of each hazard in the province. The exposure (hazard) index was determined through a spatially weighted sum of all hazards. For each municipality, the hazard index's value was calculated and normalized using Equation 1. To geo-visualized the hazard index on the map, five equal breaks were categorized as 0–0.20 (very low), 0.20–0.40 (moderate), 0.60–0.80 (high), and 0.80–1.0 (very high).

$$Haz_{norm} = (X - X_{min})/(X_{max} - X_{min}) \quad (1)$$

where: Haz_{norm} = is the normalized value of the hazard index, X = is the original value of the indicator of the municipality, X_{max} = is the highest value among all the municipalities, X_{min} = is the lowest value among all municipalities.

Seven capitals were clustered under Adaptive Capacity (AC) components such as economic, natural, human, physical, social, health, anticipatory, and institutional indicators. As shown in Table 3, the study used these indicators recommended by the Department of Agriculture—Regional Field Office. The value of the AC index was calculated and normalized using Equation 2. The same equal breaks were applied with hazards for the AC component to geo-visualized in the map as 0–0.20 (very

TABLE 2 Hazard weights used in the province of Agusan del Norte.

Hazards	Weights (%)
Typhoon	16.95
Flood	15.25
Drought	16.95
Erosion	12.71
Landslide	14.41
Storm Surge	8.47
Sea Level Rise	5.08
Salt Water Intrusion	10.17

TABLE 3 List of indicators used in measuring adaptive capacity.

Economic	Natural	Human	Physical	Social	Anticipatory	Institutional
• Poverty incidence • Inflation rate • Ag. min. wage • Total banks and financial institutions • Number of finance cooperatives • Employment in agriculture • % of farmers covered by crop insurance • Price of diesel • Cost of electricity	• % of crops irrigated • % of forest and mangroves • Agricultural production area • Presence of irrigation	• Number of private and public secondary, tertiary, and tech. vocational schools • Ratio of public school teachers to students • Literacy rate • Public and private health services • Number of public and private doctors • Health services manpower • Number of local citizens with PhilHealth • % prevalence rate of malnourished children under 7yo • Age dependency ratio	• Infrastructure investment • Infrastructure network • % of households with access to water services • % of households with access to electricity services • Number of public transport • Average farm size • Number of farm equipment/postharvest • Number of seed growers	• % of women in government • Number of registered farmer groups or unions • % of farmers who are member of registered unions/groups/coops	• No. of weather stations • Early warning system • Access to communication technology	• Number of agricultural staff • Number of farmers visited or consulted with agri-extension workers/staff

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low), 0.20–0.40 (moderate), 0.60–0.80 (high), and 0.80–1.0 (very high).

$$AC_{norm} = (X - X_{min})/(X_{max} - X_{min}) \qquad (2)$$

where: AC_{norm} = is the normalized values of the AC indicators, X = is the original value of the indicator of the municipality, X_{max} = is the highest value among all the municipalities, X_{min} = is the lowest value among all the municipalities.

All data from these sources were collated based on the methodological guidelines to include climate-risk exposure, sensitivity, and adaptive capacity. The analysis used GIS and climate modeling tools such as the CRVA, which were undertaken at the regional level down to the municipal level. The total climate risk vulnerability (CRV) was computed by adapting the vulnerability concept of Centro Internacional de Agricultura Tropical (CIAT) Southeast Asia using the formula as shown in Equation 3.

$$CRVA = \left[\left(0.15 * S\right) + \left(0.15 * E\right) + \left(0.70 * AC\right)\right] \qquad (3)$$

where CRVA = is the total climate risk vulnerability of the municipality, S = is the sensitivity of the municipality, E = is the exposure (hazards) of the municipality, AC = is the adaptive capacity of the municipality.

Documenting and analysis of CRA practices

After the climate mapping, farmers were identified to document the climate-resilient agricultural (CRA) practices in the most vulnerable areas in the Province of Agusan del Norte. The selection of these farmers was made considering their vulnerability to the prolonged flood incidence and the mitigation initiatives developed to surmount their vulnerability resulting to income increments helpful during the flood season. The documentation of the CRA practices was carried out with repeated observations in the field and personal interviews. The Municipal Agriculture Office (MAO) of Jabonga facilitated the identification of the farmers to be observed. The intelligent response of these farmers to the flooding incidence in the area caught the attention of the MAO, which led to the farmers' involvement in the project as reference for the CRA practices.

Two farmer-groups were chosen for close observation. One farmer group was assigned as without CRA and another farmer group as with CRA. Seven farmers had been observed under without CRA, who were selected from the barangays of Colorado, Magsaysay and Libas, including the población barangay of Jabonga. For the farmer group of with CRA, the same barangays were the areas considered for the farmer selection. Furthermore, the farmers under the "with CRA" group were divided into two—those combining corn with squash through a well-timed alternate monocropping and intercropping system and those practicing well-timed crop rotation of corn, rice and green corn. The timing of these farming systems was based on the anticipation of rains and flood incidence.

The case study involved five (5) farmers for the alternate monocropping and intercropping system where corn monocropping was adopted in the first cropping season and corn-squash intercropping was done in the second cropping season. In this particular farming system, the squash output was not intended for sale in the market primarily but rather as feed for the hogs during the rainy season. However, the farmers could use their squash product for sale in the market, for household consumption, and for their hogs. The second farming system of crop rotation involved another five (5) farmers for observation. All of their produce were intended for market to obtain additional income to cope with the difficult times during the flood season. The observation period was for two cropping seasons. Data from field observations and interviews were analyzed using cost accounting and cost-benefit analysis (CBA). Means or average values were used in the CBA.

Results and discussion

Climate risk vulnerability assessment (CRVA) of selected major crops in Agusan del Norte

Sensitivity index

Changes in climatic suitability of the selected priority crops in Agusan del Norte (rice, corn, and banana) due to climate change by the year 2050 through climate **modeling** and the use of species distribution model was mapped out (Apdohan et al., 2021). Several areas in the province have increasing climatic suitability while some have relatively the same sensitivity index due to changes in precipitation and temperature for rice. These are exhibited in some parts of the province except in Butuan, Buenavista, and Carmen. It is, however, misleading to conclude that crops in geographic areas experiencing a decrease in climate suitability will not survive. A reduction in yield is, however, expected in high-impact areas. Since the climate is predictable but not controllable, an improved crop production practices system that promotes healthy soil and efficient use of water is vital as a means of climate change (Palao et al., 2017).

Corn crop simulation in the province, on the other hand, shows decreased climate suitability. The results indicate the need for improvement in crop management, better provision and optimization in the utilization of water for irrigation and increase adaptation strategies to cope with the increasing climatic pressures that might affect agricultural productivity.

Hazard index

Six (6) hazards were identified in the said province, namely: flood, tropical cyclone, sea level rise, storm surge, landslide, and erosion. A high incidence of tropical cyclone was noted in the northern part of the province compared to other municipalities located in the southern part (Apdohan et al., 2021). Higher exposure incidence to sea level and storm surge are also observed in Butuan City since this area sits below sea level (UNISDR, 2013). On the other hand, the municipality of Jabonga is most exposed to flooding based on the geographical setting, since this area is the main outlet of Lake Mainit where all the river tributaries in the adjacent municipalities empty into this area causing a significant overflow of the lake. Elevated areas have high exposure to landslide and erosion. Overall exposure results show a higher incidence of hazards in the municipalities of Jabonga and Santiago in the Province of Agusan del Norte.

Adaptive capacity index

Butuan is the most adaptive municipality within the province concerning economic, natural, social, human, physical, anticipatory, and institutional. This suggests that Butuan has excellent coping mechanisms and strategies to respond to climate-related hazards. Butuan, being a local government unit with high income, has developed climate-resilient agricultural villages that have the higher adaptative capacity to flooding and other climate risks. Climate-Smart Villages (CSV) approach has a high probability of scaling out climate-smart agricultural technologies, practices, and services fit to the given conditions (Aggarwal et al., 2018). However, most municipalities across the study sites have a very low index concerning human capital. The overall capacity index shows that 9 out of 12 or 75% of the total number of municipalities have a low adaptive capacity index. This indicates the need for the local government units to focus on improving their coping mechanisms by adding or increasing their services and interventions in the respective communities affected by climate-related pressures.

Total CRVA

The vulnerability model was constructed using the GIS platform to pre-process the spatial and aspatial datasets for the three components such as sensitivity, exposure, and adaptive capacity to come with the total climate risk vulnerability assessment (CRVA). The total CRV for rice and banana shows that municipalities were identified as highly vulnerable (Figure 1).

A twin climate risk vulnerability assessment index result was observed for rice and banana production. The twin index for the two crops is within the standard ranges. On the other hand, the CRVA model result for corn shows that there was a high vulnerability in most municipalities due to the divergence of high exposure to hazards, lower climate suitability of crop in the future, and low adaptive capacity. The radar graphs show the influence of the hazard, sensitivity, and adaptive capacity on the vulnerability status of the municipalities in Agusan del Norte.

The issues and the climate resilient agriculture (CRA) practices

The issues related to climate change in the Province of Agusan del Norte in Caraga Region are shown in Table 4. Across Agusan del Norte, rice, coconut, banana, abaca, and corn are the major crops grown. The agricultural development officers in the province identified these crops and associated the climate risks that adversely affected the production of these crops annually. The adverse effects of these climate risks led to reduced yield and income that would diminish the adaptive capacity of the farmers, especially during the flooding season. As shown in the table, flooding due to typhoons and continuous rain is the major challenge in the production of these crops across the province. Drought is also a climate risk to reckon with, particularly in the production of rice and corn. However, most of the climate change issues are the consequences of typhoons and flooding, in which pest and diseases, soil erosion, siltation and water logging are the resulting problems for the farmers. The agricultural development officers also identified the outcomes of experiencing the climate change issues and problems as destructive to the said crops that would eventually reduce the potential income from the crop yield. Typhoons could flatten the field and submerge the crops with a surge of water. Drought could damage as well through the emergence of pests and diseases as shown in the table. Additionally, floods could kill farm animals that become a source of dismay among the farmers. Toward these climate change impacts and issues, the CRA practices had been observed for farmers to learn some viable options to surmount the challenges of such devastating natural occurrences.

Climate resilient agriculture (CRA) practices: The case of Jabonga, Agusan del Norte

Climate change impacts can devastate tracts of croplands, which can put the welfare of a farming household at risk. In Jabonga, Agusan del Norte, Philippines, these impacts have been manifested in heavy rains and typhoons resulting to long flooding episodes and inundation for at least 2 weeks to 3 months in the maximum. In Chart C of Figure 1, corn is in great danger among the major crops to these climate change impacts, in which under such impacts corn is faced with high climate hazard and sensitivity potential. This also forms the major reason for the highlight of corn in this section. With the

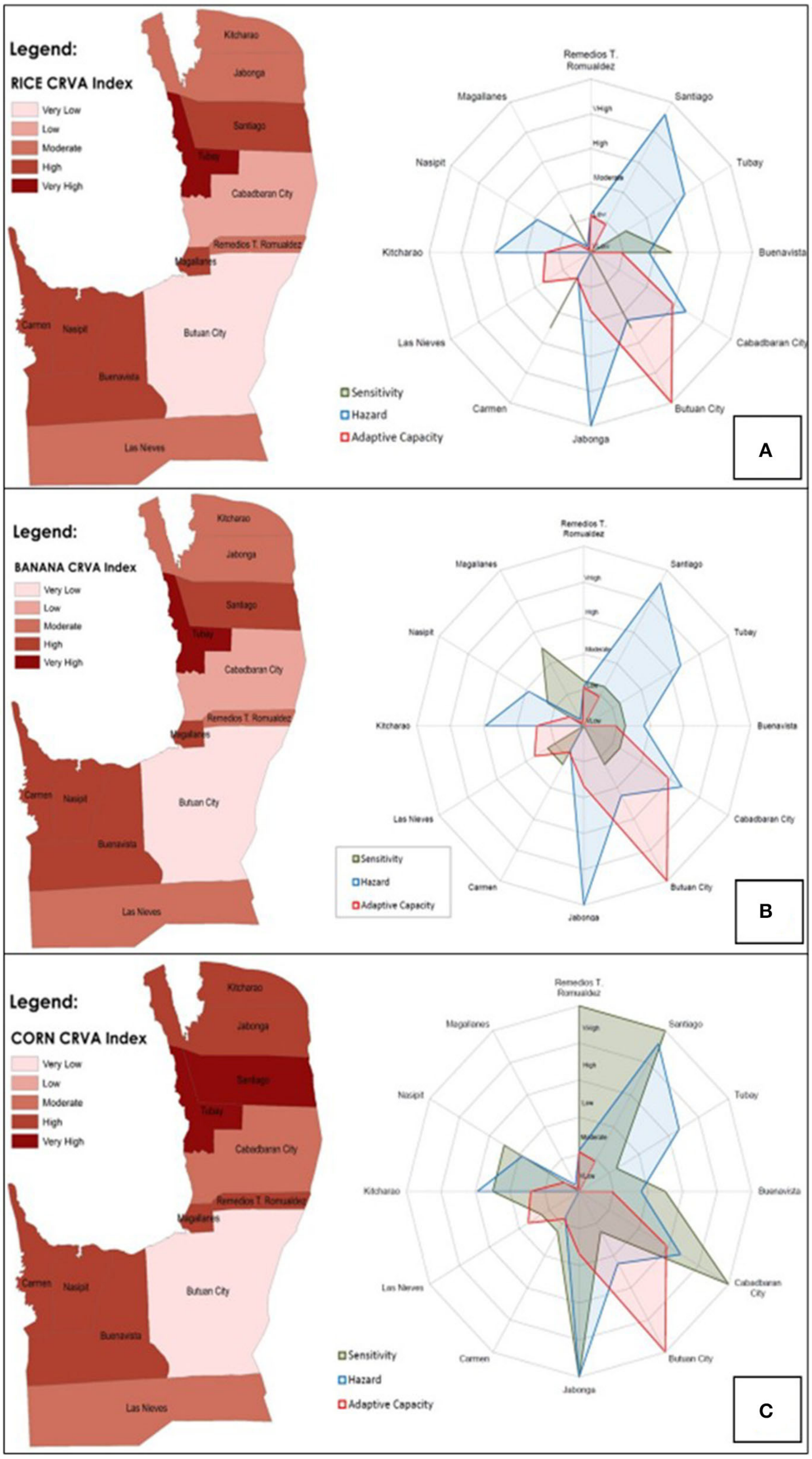

FIGURE 1
Climate Risk Vulnerability Index Map in Agusan del Norte for **(A)** rice; **(B)** banana; and **(C)** corn.

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TABLE 4 List of issues and the CRA practices in response to climate change for the primary and secondary crops and livestock.

Crops	Climate Change Impacts	Flood/ Continuous Rain	Typhoon	Drought
Rice	Typhoon, flood, pests and diseases, drought	• Reduce yield • Delayed harvesting • Pests and diseases infestation increase • Submerge crops resulting to low or washing out of newly harvested palay • Stunted growth • Low germination • Seed in the seedbeds are washed out • Fishing paraphernalia damaged/ washed out • Livestock washed out, high mortality	• Lodging the crops • Reduced yield • Lake mainit overflow causes submergence of crops around the lake • Cause siltation	• Reduced yield • Stunted growth • Occurrence of pests and diseases
Coconut	Typhoon, soil erosion, siltation, flood, continuous rain			
Banana	Typhoon, soil erosion, siltation, flood, continuous rain			
Abaca	Typhoon, soil erosion, siltation, flood, continuous rain, water logging, pests/diseases			
Corn	Typhoon, flood, pests and diseases, drought, water logging, erosion, siltation			

high potential for climate hazard and sensitivity to it, some of the corn farmers in the area have tried to adapt by adjusting their farming system to enable them to gain more income and resources to be used during the economically paralyzing flooding episode.

Climate hazard for CRA: Heavy rains and massive flooding

Jabonga is a municipality located near Lake Mainit, the fourth largest lake in the Philippines, and in Caraga Region where the pronounced climate pattern is characterized to be wet and very wet. The location of the Caraga Region in the Pacific Seaboard contributes to the unpredictable weather condition in Jabonga, Agusan del Norte. Every year, heavy rains and typhoons visit the area, bringing so much moisture and water to cause massive flooding and inundation of at least a meter high especially for the barangays of Colorado, Magsaysay and Libas, including the village in the center of Jabonga municipality. During this time of inundation, the water from the contiguous lake breaches into these barangays, challenging the draining out the flood waters. Fish species from the lake get into the flooded areas, but the agricultural fields are put under water for at least 2 weeks to 3 months at most every year. Boats (sometimes with motor) and rafts turn to become the means of transportation within the vicinities of the affected barangays. To salvage the lost opportunities during the time of inundation, the farmers resort to the practices of alternate monocropping and intercropping system for corn and squash, and of crop rotation for corn, rice and green corn. Those practices are presented here to be more preferrable than the conventional two-season monocropping for corn, due to added income and resources that can be used during the inundation period. The following are the observed practices and benefits from such cropping systems as a means of adapting to the dominant climate change impacts in the area.

FIGURE 2
Corn-squash/corn crop rotation in Agusan del Norte.

Climate resilient agriculture (CRA) 1: Corn-squash/corn alternating monocropping and intercropping

Alternating monocropping and intercropping prior to the incidence of flood in the aforementioned barangays of Jabonga, Agusan del Norte may be a time-tested strategy to cope with climate change impacts of heavy rains and typhoons among the farmer adopters. With proper timing that is done by weather observation and listening to the weather advisories of the Philippine Atmospheric, Geophysical and Astronomical Space Administration (PAGASA) of the Department of Science and Technology (DOST), it ensures crop harvest capable to provide the farming households with income and resources to use during the flooding episode due to climate change. Thus, it is a production system that provides an economic buffer during times of inundation in the area.

The practice allows the farmers to produce corn for two straight seasons (March–June and July–November) and squash (July–November) (Figure 2). Flood usually sets in during December–February, which is evaded by such production timing. No crop production occurs during the flood season, enabling the farming household to evade crop losses, produce

TABLE 5 Cost and benefit comparison of the well-timed pure monocropping and the well-timed alternate monocropping and intercropping.

Climate-smart Agriculture 1: Alternate Monocropping and Intercropping System + Production Timing during Flood Occurrence

Well-timed Farmer's Practice of Monocropping vs. Well-timed Alternate Monocropping and Intercropping System	Without CRA: Farmers produce corn for two seasons to avoid losses from inundation of 2–3 months.				
Particulars	**Average Volume or Amount/ha**	**Average Unit Price (Php, USD)**	**No. of Cropping Periods/Year**	**Total Volume or Amount Used/Year**	**Value/Year**
Outputs					
Corn (kg)	3,742	15.14 (*0.30*)	2	7,484	113307.76 (*2207.87*)
Squash (kg)					
Total Value (Benefit)					113307.76 (*2207.87*)
Inputs					
Labor, planting (man-day)	14	300 (*5.85*)	2	28	8,400 (*163.68*)
Labor, spraying (tank)					
Labor, fertilization (man-day)	3	300 (*5.85*)	2	6	1,800 (*35.07*)
Labor, corn harvesting (man-day)	8	300 (*5.85*)	2	16	4,800 (*93.53*)
Labor, squash harvesting (man-day)					
Labor, corn hauling (service package)	3	500 (*9.74*)	2	6	3,000 (*58.46*)
Labor, squash hauling (service package)					
Herbicide (pack)					
Pesticide (liter)					
Fertilizers, urea (bag)	2	980 (*19.09*)	2	4	3,920 (*76.38*)
Fertilizers, complete (bag)	2	1,200 (*23.38*)	2	2	4,800 (*93.53*)
Fertilizers, potash (bag)					
Fertilizers, sulfate (bag)					
Seeds, corn (kg)	25.14	50 (*0.97*)	2	50.28	2,514 (*48.99*)
Seeds, squash (can, 250 g)					
Farm equipment use (total package cost)	5,200 (*101.33*)		2		10,400 (*202.65*)
Irrigation (package)	1	180 (*3.51*)	2	2	360 (*7.01*)
Shelling fee (bushel)	213	9.8 (*0.19*)	2	426	4,174.8 (*81.35*)
Total Value (Cost)					44168.8 (*860.65*)
Net Benefit					69138.96 (*1347.21*)
Well-timed Farmer's Practice of Monocropping vs. Well-timed Alternate Monocropping and Intercropping System	**With CRA: Farmers produce corn for two seasons as well. However, in the second season, corn is intercropped with squash. During inundation, squash is used as a feed for hogs that are eventually sold. The estimated value of the squash approximates its contribution to the potential income earned by the household.**				
Particulars	**Well-timed Alternate Monocropping and Intercropping (per cropping)**				
	Average Volume or Amount/ha	**Average Price/kg (Php, USD)**	**No. of Cropping Periods/Year**	**Total Volume or Amount Used/Year**	**Value/Year**
Outputs					
Corn (kg)	1st season: 3,742 2nd season: 2,350	15.14 (*0.30*)	2	6,092	92232.88. (*1797.21*)

(Continued)

TABLE 5 Continued

Well-timed Farmer's Practice of Monocropping vs. Well-timed Alternate Monocropping and Intercropping System	**With CRA: Farmers produce corn for two seasons as well. However, in the second season, corn is intercropped with squash. During inundation, squash is used as a feed for hogs that are eventually sold. The estimated value of the squash approximates its contribution to the potential income earned by the household.**				
Particulars	**Well-timed Alternate Monocropping and Intercropping (per cropping)**				
	Average Volume or Amount/ha	**Average Price/kg (Php, USD)**	**No. of Cropping Periods/Year**	**Total Volume or Amount Used/Year**	**Value/Year**
Squash (kg)	4,591	3 (*0.06*)	1	4,591	13773 (*268.37*)
Total Value (Benefit)					106005.88 (*2065.59*)
Inputs					
Labor, planting (man-day)	14	300 (*5.85*)	2	28	8,400 (163.68)
Labor, spraying (tank)	13	30 (*0.58*)	1	13	390 (*7.6*)
Labor, fertilization (man-day)	4	300. (*5.85*)	2	4	2,400 (*46.77*)
Labor, corn harvesting (man-day)	3	275 (*5.36*)	2	3	1,650 (*32.15*)
Labor, squash harvesting (man-day)	3	280 (*5.46*)	1	3	840 (*16.37*)
Labor, corn hauling (service package)	1	500 (*9.74*)	2	1	1,000 (*19.49*)
Labor, squash hauling (service package)	1	560 (*10.91*)	1	1	560 (*10.91*)
Herbicide (pack)	2	160 (*3.12*)	1	2	320 (*6.24*)
Pesticide (liter)	2	325 (*6.33*)	1	2	650 (*12.67*)
Fertilizers, urea (bag)	1	960 (18.71)	1	1	960 (18.71)
Fertilizers, complete (bag)	1	1,200 (*23.38*)	1	1	1,200 (*23.38*)
Fertilizers, potash (bag)	1	440 (*8.57*)	1	1	440 (*8.57*)
Fertilizers, sulfate (bag)	2	650 (*12.67*)	1	2	1,300 (*25.33*)
Seeds, corn (kg)	17.57	50 (*0.97*)	2	35.14	1,757 (*34.24*)
Seeds, squash (can, 250 g)	1	1,818 (*35.42*)	1	1	1,818 (*35.42*)
Farm equipment use (total package cost)	4,700 (*91.58*)		1		4,700 (*91.58*)
Irrigation (package)	1	180 (*3.51*)	1	1	180 (*3.51*)
Shelling fee (bushel)	180	10.6. (*0.21*)	2	180	3,816 (*74.36*)
Total Value (Cost)					32381. (*630.96*)
Net Benefit					73624.88 (*1434.62*)
Estimated increment with CRA	(73624.88-69138.96)	4486.92			

Figures in parentheses and in italics are in USD. The exchange is USD1 = Php51.32.

income prior to flood, and set aside some amounts for saving. During the second cropping, corn is the market-oriented output, while the squash is not necessarily for sale. The squash is stored to be used as feeds for hogs. The hogs are raised until the households see them good for sale. To raise hogs during the flood season, the households use to transfer their hogs to elevated areas where other indigenous feed materials can be found such as pseudo stems of bananas. To get through the flood season, the households can sell the hogs to provide additional income for their daily needs. This practice is common in Barangay Colorado where the flood incidence can keep the area under water for 2–3 months.

Through the CRA practice, the farmers can adapt to flooding in the area for months. It helps the farming households minimize losses through calculated evasion of flood devastation. With this CRA practice, crop production continues to support the farmers' livelihood despite the disruption from flooding in the area. The practice of alternate monocropping and intercropping for corn and squash is adaptive for climate change impacts, which provides resilience to the farming households. The farmers can wait for the floods to drain out to engage in farming again. In Table 5, the said practice saves the farming households with the incremental net benefit of around Php4,500 or USD87 per hectare per year compared

TABLE 6 Cost and benefit comparison of the well-timed pure monocropping and the well-timed crop rotation of corn, rice and green corn.

Climate-smart Agriculture 2: Crop Rotation Prior to Flooding

Well-timed Farmer's Practice of Monocropping vs. Well-timed Crop Rotation of Corn, Rice and Green Corn Production	**Without CRA: Farmers produce corn for two seasons to avoid losses from inundation of 2–3 months.**				
Particulars	**Average Volume or Amount/ha**	**Average Unit Price (Php, USD)**	**No. of Cropping Periods/Year**	**Total Volume or Amount Used/Year**	**Value/Year**
Outputs					
Corn (kg)	3,742	15.14 (*0.30*)	2	7,484	113307.76 (*2207.87*)
Rice (kg)					
Green corn (kg)					
Total Value (Benefit)					113307.76 (*2207.87*)
Inputs					
Labor, rice planting (man-day)					
Labor, corn planting (man-day)	14	300 (*5.85*)	2	28	8,400. (*163.68*)
Labor, herbicide application (man-day)					
Labor, fertilization (man-day)	3	300 (*5.85*)	2	6	1,800 (*35.07*)
Labor, corn harvesting (man-day)	8	300 (*5.85*)	2	16	4,800 (*93.53*)
Labor, green corn harvesting (man day)					
Labor, rice harvesting (man-day)					
Labor, corn hauling (service package)	3	500 (*9.74*)	2	6	3,000 (*58.46*)
Labor, green corn hauling (service package)					
Labor, rice hauling (service package)					
Labor, rice threshing (service package)					
Fertilizer, rice urea (bag)					
Fertilizers, corn urea (bag)	2	980 (*19.09*)	2	4	3,920 (*76.38*)
Fertilizers, complete (bag)	2	1,200 (*23.38*)	2	2	4,800 (*93.53*)
Seeds, corn (kg)	25.14	50 (*0.97*)	2	50.28	2,514 (*48.99*)
Seeds, rice (bag)					
Farm equipment use (total package cost)	5,200 (*101.33*)		2		10,400 (*202.65*)
Irrigation (package)	1	180 (*3.51*)	2	2	360 (*7.01*)
Shelling fee (bushel)	213	9.8 (*0.19*)	2	426	4174.8 (*81.35*)
Total Value (Cost)					44168.8 (*860.65*)
Net Benefit					69138.96 (*1347.21*)
Well-timed Farmer's Practice of Monocropping vs. Well-timed Crop Rotation of Corn, Rice and Green Corn Production	**With CRA: Farmers have to rotate their production before the flooding season. The commodities to be rotated are corn, rice and green corn.**				
Particulars	**Average Volume or Amount/ha**	**Average Price/kg (Php, USD)**	**No. of Cropping Periods/Year**	**Total Volume or Amount Used/Year**	**Value/Year**
Outputs					
Corn (kg)	3,742	15.14 (*0.30*)	1	3,742	56691.3 (*1104.66*)
Rice (kg)	4,020	16.5 (*0.32*)	1	4,020	66330 (*1292.48*)
Green corn (kg)	4745.67	5.25 (*0.001*)	1	4754.67	24914.77 (*485.48*)

(Continued)

TABLE 6 Continued

Well-timed Farmer's Practice of Monocropping vs. Well-timed Crop Rotation of Corn, Rice and Green Corn Production	With CRA: Farmers have to rotate their production before the flooding season. The commodities to be rotated are corn, rice and green corn.				
Particulars	**Average Volume or Amount/ha**	**Average Price/kg (Php, USD)**	**No. of Cropping Periods/Year**	**Total Volume or Amount Used/Year**	**Value/Year**
Total Value (Benefit)					147936.07 (*2882.62*)
Inputs					
Labor, rice planting (man-day)	6	300 (*5.85*)	1	6	1,800 (*35.07*)
Labor, corn planting (man-day)	14	300 (*5.85*)	2	28	8,400 (*163.68*)
Labor, herbicide application (man-day)	1	300 (*5.85*)	3	3	900 (*17.54*)
Labor, fertilization (man-day)	2	300 (*5.85*)	3	6	1,800 (*35.07*)
Labor, corn harvesting (man-day)	8	300 (*5.85*)	1	8	2,400 (*46.77*)
Labor, green corn harvesting (man day)	8	300 (*5.85*)	1	8	2,400 (*46.77*)
Labor, rice harvesting (man-day)	7	300 (*5.85*)	1	7	2,100 (*40.92*)
Labor, corn hauling (service package)	3	500 (*9.74*)	1	3	1,500 (*29.23*)
Labor, green corn hauling (service package)	1	500 (*9.74*)	1	1	500 (*9.74*)
Labor, rice hauling (service package)	10	300 (*5.85*)	1	10	3,000 (*58.46*)
Labor, rice threshing (service package)	5	1,105 (*21.53*)	1	5	5,525 (*107.66*)
Fertilizer, rice urea (bag)	2	960 (*18.71*)	1	2	1,920 (*37.41*)
Fertilizers, corn urea (bag)	1	960 (*18.71*)	2	2	1,920 (*37.41*)
Fertilizers, complete (bag)	2	1,200 (*23.38*)	3	6	7,200 (*140.3*)
Seeds corn (kg)	25.14	50 (*0.97*)	2	50.28	2,514 (*48.99*)
Seeds, rice (bag)	1	1,400 (*27.28*)	1	1	1,400 (*27.28*)
Farm equipment use (total package cost)	7,950 (*154.91*)		1.5		11,925 (*232.37*)
Irrigation (package)	1	180 (*3.51*)	1	1	180 (*3.51*)
Shelling fee (bushel)	180	10.6 (*0.21*)	1	180	1,908 (*37.18*)
Total Value (Cost)					59292 (*1155.34*)
Net Benefit					88644.07 (*1727.28*)
Estimated increment with CRA			19505.11 (*380.07*)		

Figures in parentheses and in italics are in USD. The exchange is USD1 = Php51.32.

to the most common and considered as the conventional practice of monocropping. The estimated net increment from the CRA practice may be the least since the farming households can sell their hogs speculatively to earn more income. There may be additional expenses incurred due to the integration of squash in the area, but these additional expenses are recouped from the additional benefits with this CRA.

Climate resilient agriculture (CRA) 2: Corn-rice-green corn crop rotation

Crop rotation is known to have beneficial effects on crops, especially since it promotes biodiversity conservation and protects the crops from pests and diseases as well. For some farmers in the affected areas of Jabonga, Agusan del Norte, the consequences of the risk associated with annual flooding are painful, which must be dealt with ingenuity. In this practice of crop rotation, the farmers can potentially earn better as shown in the succeeding (Table 6). With the flooding incidence seemingly occurring in the same period of the year, the farmers have learned to accept reality and have developed adaptations. The CRA practice of rotating crops and adjusting the production timing to suit the onset and end of flood in the area has been the practice of the farmers to survive the flood episode with minimal worry and anxiety. Observance of the flood patterns and crudely analyzing the flood damage have guided the farmers in configuring adaptations.

The CRA practice of crop rotation in this particular case is with a strong consideration of the proper timing of planting and harvesting. The first cropping is the production of corn grain, followed by the production of rice and the shorter green corn cropping (Figure 3). Green corn is opted as the last crop of this

FIGURE 3
Corn-rice-green corn production rotation in Agusan del Norte.

crop rotation strategy in anticipation of the start of rains and floods or inundation, the corn is cut short in production to grow only for 60–70 days for green corn production. This strategy allows the farmers to gain higher income than grain corn as the green corn sells higher at an earlier harvest time than the normal harvesting at 110 days after planting for grain corn. This allows the farming households to earn income from three sources: corn grain, rice and green corn. Table 5 specifies the potential benefits and costs per hectare per year. The conventional farming of corn (monocropping) is again compared to this CRA to evaluate the potential net benefit. As shown in Table 5, the expense items incurred in carrying out the entire cropping system of this CRA is increased, since rice and corn have different input requirements for their production. However, Table 5 shows that the net benefit or incremental benefit from this CRA is much larger than the earlier CRA. The superiority of the second CRA is shown here to generate an increment of around Php19,500 or USD380 per hectare per year (Table 5). The amount is considered a substantial buffer for the farming household to get through the flood incidence and begin farming again after the flood.

Conclusion

Climate change impacts have been already experienced across Caraga Region, particularly in the province of Agusan del Norte. The major crops grown in the province are adversely affected by these impacts, wherein their sensitivity and their degrees of climate hazards are estimated to be substantial. The climate mapping using the GIS and other tools have proved that the potential impacts of climate changes can be estimated to show the potential hazards and sensitivities of the crops grown in the area as well as the potential adaptive capacity of their agricultural producers. Furthermore, this study shows that the farmers can develop their adaptive capacities to mitigate the impacts of climate change. As shown in the earlier section, the farmers can confront adverse climate change impacts with their ingenuity. The farmers have made changes to their usual or common practices that enable them to earn additional income and resources to be used during the time when inundation in the area happens. This study has shown that the same changes can be implemented by the farmers of other crops to be able to withstand and adapt to the adverse impacts of climate change. The CRA practices highlighted here show that these are superior to the conventional farming practices even though there are additional cost items to confront.

On the other hand, the involvement of the local providers of technical support to agriculture enhancement are vital in strengthening the local capacity for Climate Resilient Agriculture (CRA) particularly in investment planning using climate risk maps. The local technologists are exposed to participatory climate risk mapping and assessing the cultural practices in farming and fishery to avoid the impacts of climate change. The maps of climate risks generated for the Province of Agusan del Norte serve as the basis for CRA investment planning. The maps on sensitivity, hazard, and adaptive capacity are useful inputs in investment planning for adaptation to climate change and creating climate-resilient agriculture. These maps guide farmers and the local technologists to improve the adaptive mechanisms or strategies of the farming communities to respond to climate-related hazards. Most municipalities across the study sites have a low adaptive capacity index. The results imply the need for the local government units to focus on improving their adaptive mechanisms by increasing their services and interventions to tackle climate-related pressures. Adaptive mechanisms to overcome the flood risks in Jabonga include corn-squash/corn crop rotation and corn-rice-green corn production rotation. The benefit of using adaptive approaches over the usual practice of crop production following the normal production calendar is not only on the economic aspects but also on the psychosocial side because farmers are given safety nets.

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

RV responsible for the overall concept of the study. RB is responsible in working on the economics aspect of the study, in determining the cost-benefit analysis (CBA) including the sensitivity analysis. AA contributed to the geospatial assessment and mapping of the areas vulnerable to climate change. He is responsible for performing the climate risk and vulnerability analysis using Maxent for the climate risk and vulnerability mapping.

All authors contributed to the article and approved the submitted version.

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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.

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Food security systems in rural communities: A qualitative study

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Indonesia is rich in natural resources, but the problem of food insecurity is still a significant concern. However, few studies still examine the relationship of socio dynamics in contributing to local ecosystems to create food security. In this study, we discuss how social dynamics contribute to normative structures, community habits, and livelihoods to meet the living needs of rural communities in creating household food security and how they try to deal with worsening food insecurity through the local wisdom of rural communities. The research methodology is participatory qualitative, while data collection is through a Discussion Group Forum (FGD) and in-depth interviews with rural communities. Fifteen villages contributed to this study, interviewing 14 villagers individually, and the rest were grouped in FGDs based on livelihood categories and equal access to forest and coastal areas. Interview notes and transcription of citations were analyzed using the Thematic Framework Analysis (TFA). The study results illustrate that the village food system is vulnerable to human and natural capital. An adaptation of rural communities will experience food security difficulties when ecosystems do not provide sufficient protection due to a fluctuating climate, crop failure, and loss of household labor due to travel and health emergencies. In addition, food security is created through the dynamics of a well-maintained environment and rural local wisdom, which facilitates broad access to food provided by nature, agricultural land, marine resources, environmental knowledge, community relations, and labor. Our findings highlight the need for interventions that promote environmental conservation goals and introduce social structures that support food security.

KEYWORDS
coping methods, food security, subsistence farming, rural communities, Indonesia

Introduction

Food security remains a global goal, defined as achieving sufficient access to nutritious food for healthy growth (Banik, 2019). Data shows that 149 million children suffer from food insecurity worldwide (Khadija et al., 2022), one of the variables is the lack of adequate nutritional intake for child growth and development; until now, it is still a world problem (Bailey et al., 2015). The implementation of sustainable food security policies in Indonesia has ordered every province to address the issue of malnutrition by protecting ecosystems (Damanik, 2018). There is a consensus that further research is needed to understand better the role of natural ecosystems in developing food security systems for vulnerable communities, such as the poor, pregnant women, and children (Powell et al., 2015; Cruz-Garcia et al., 2016).

The results of previous studies have shown that natural ecosystem products support the regular functioning of food systems by providing a wide variety of food and nutritional intakes, as well as providing livelihoods for rural communities (Powell et al., 2015). In addition, research conducted in tropical forests shows that rural communities are more likely to consume a varied diet than those who mostly rely on buying food at the market (van Vliet et al., 2015). Significant resources, such as vegetables and fruits, can be obtained freely from nature; abundant natural resources enable people to generate income, such as ecotourism, fishing for sale, and farming (Cruz-Garcia et al., 2016).

The specific role of natural ecosystems in creating food security is still challenging. Food security is a condition that improves, such as food availability, or a person can eat their favorite food, thus avoiding hunger that can occur over a certain period (FAO, 2017). In the context of the contribution of nature as part of daily food security, it still seems to be an exciting thing to study, given the realities that exist in society, for example harvesting wild vegetables is not only a daily activity but can also reflect the level of food availability that is deteriorating depending on the environment and social acceptance of harvested items (Powell et al., 2015; Paumgarten et al., 2018). Meanwhile, in the context of adaptation to climate change, the current use of natural ecosystems as a mechanism for meeting the needs of life is expected to safeguard natural resources for future life because natural threats often occur, and the community gradually adopts steps to manage risks (Eriksen et al., 2005; Berman et al., 2012). Therefore, testing the contribution of natural resources in meeting food security requires a comprehensive study of resources and practices carried out by communities through several food security scenarios (Pramova et al., 2012; Powell et al., 2015).

In addition, it is also necessary to examine the contribution of food from natural resources to assess steps in creating food security because dependence on nature and livelihood practices can sometimes be a "poverty trap" (Paumgarten et al., 2018) which leads to increased vulnerability to natural disasters, such as droughts and floods. Such challenges usually force someone to sell their assets to make ends meet and increase the extraction of natural resources. In addition to reducing the availability of natural resources, this last problem will also impact the community regarding natural hazards due to ecosystem degradation (Ferse et al., 2014). In addition, despite having rich natural ecosystems and being easy to access, problems for vulnerable communities such as the poor are usually difficult to have an asset base to utilize sufficient varieties of natural resources (Paumgarten et al., 2018) or to invest in high-return ventures (Brouwer et al., 2007; Orsini et al., 2013).

This study further discusses the function of natural ecosystems in helping rural communities create food security by looking at the social dynamics that affect rural areas in Bone Regency, Indonesia. This study examines two problems; first, the extent to which adaptation to natural ecosystems supports the food security system in the village; secondly, the factors that influence how communities can benefit from natural ecosystems when food insecurity occurs in the village.

The scope of this research is to explain the social dynamics that make a beneficial contribution to the ecosystem toward the creation of food security in the village (Grote, 2014) because the community, on average, uses natural products (more than 85%), the population density is low, good access to nature, and lack of extractive activities directed at markets (Ramirez-Gomez et al., 2015). These variables are combined to describe an "ideal" case scenario (Yin, 2009), which serves to ascertain the role of natural resources in creating food security among communities whose food systems and livelihoods are well adapted to their environment (Paumgarten et al., 2018).

This research is related to the social dynamics in which people's livelihoods are related to subsistence in highland and lowland areas that are rich in biodiversity, especially in Bone Regency. This research believes collaboration between humans and nature to create food security is very much needed. While recent efforts have been made to produce policies related to environmental changes caused by global warming (Schuldt and Roh, 2014), topics such as these often ignore problems of rural communities that have not been addressed directly (Jang and Hart, 2015). Food security is a constitutive part of the reality of society; for example, a health and demographic survey found that Indonesia was ranked fifth in the prevalence of stunting in the world, and the results of research from Basic Health Research in 2013 showed the prevalence of stunting was 37.2%, including health problems who are heavy because they are in the range of 30–39% (Hadi et al., 2019). In addition, data from the Meteorology, Climatology, and Geophysics Agency shows that floods and droughts occur periodically in Indonesia (Pratiwi et al., 2016), and climatic conditions indicate seasonal weather patterns change in the region. In addition, conservation models highlight that areas rich in biodiversity may face extinction threats from other sites, as intensive deforestation can further affect sensitive plant and animal species (Joetzjer et al., 2013).

We assess food security through group discussions about the supports that affect food access and the adaptation mechanisms they adopt. We apply the concept of "strategy," which is the response adopted to deal with the constraints experienced in the social structure of society, such as knowledge and management systems (Bacon et al., 2012). This structure includes cultured adaptation to the environment that helps to cope with disasters, known as "adaptive strategies" (Schlueter et al., 2012). The literature on coping behavior is considered an appropriate indicator of food security. A comparison of previous studies found that coping strategies reflect worsening conditions of food insecurity as individuals seek to balance their food needs with increased income (Harvey et al., 2014). Families usually take advantage of available resources (such as wild food) when food insecurity is mild. However, as food scarcity worsens, unsustainable ways to access food become more common, such as selling their assets (Kimani-Murage et al., 2014). Survival strategies such as fasting foreshadow problems to overcome. Transitions in the face of short-term food insecurity, for example, the livelihood systems of landless freelancers, are likely to experience hunger quickly when they are out of work for several days. In turn, the absence of a food insecurity type coping strategy despite a disaster indicates that the food security system can recover quickly to avoid the collapse of local livelihoods.

This research frames studies related to sustainable livelihoods (Serrat, 2017), using a qualitative lens to explain the socio-economic dynamics that affect the food security of rural communities, which are described in economic activities, lifestyles, and types of identities (Rigg, 2007). This approach contributes to a shift in the understanding of livelihoods from accumulating money and tangible goods to immaterial, like social connections, forms of association, and traditional knowledge (Reyes-Garcia et al., 2008). This study pays special attention to rural communities because they are subject to several social arrangements, such as village norms that regulate people's lives and the political economy related to the state. Such circumstances may be necessary as the ability of rural communities to benefit from agriculture may be limited by official constraints such as conservation rules (van Vliet et al., 2015) or informal barriers such as social prejudice (Kuhnlein et al., 2013).

Strand of concern

The study was conducted in Bone Regency, South Sulawesi Province, Indonesia. It comprises five sub-districts containing fifteen villages (Figure 1). The area has experienced substantial population growth in recent years. Indonesia's 2010 census reported 238 million people, while 2020 found 270 million people (Wardaningsih, 2021), with a land area of 1.9 million square kilometers, so the population density is 141 people per square kilometer.

The annual temperature varies from 26.6 to 27.0°C, while the annual rainfall ranges from 2,000 to 4,000 mm (Supriadi et al., 2019). Natural forests occupy more than 58 percent of Indonesia's territory, with no significant deforestation documented in the last decade (Mawardi, 2019). There are two seasons: wet (October–February) and dry (March–September). The highest river elevation and discharge in Bone Regency occurred in January and February (Dwiyanto et al., 2016). Bad weather events occurred seasonally, such as prolonged droughts in 1972, 1997, and 2019, while major floods occurred in 2003 and 2021. During the drought period, water discharge was around 30–50% lower than usual, whereas during the rainy season water discharge is higher than normal, ranging from 40 to 90% more than the average (Apriani et al., 2018).

Village government administrators are village heads assisted by village officials as elements of government administration. The villagers directly elect the village head through village head elections. The village already has electricity and running water and already has sanitation. For education, the village already has Elementary School, but Junior High School and Senior High School are still limited, and the majority are only found in the city. Rural communities' primary income sources are agriculture, fisheries, and livestock (Ray et al., 2021). Several types of agricultural land were carried out on highland and lowland plots. Rice and cocoa are grown in the lowlands, while corn is mainly grown in the highlands. Onions, carrots, cucumbers, eggplant, tomatoes, and spinach are intercropped. Households consume most of the agricultural products.

The fisherman's produce is also used for household consumption, although occasional sales are expected. Types of fish, such as tuna, skipjack, snapper, and *Decapterus*, are widely sold in the city market. In addition, some households also raise livestock, such as poultry. Paid agricultural labor also exists, but the work is usually short-term. Some of the reported forms of non-agricultural labor wages include (1) non-professional services (e.g., construction); (2) administrative work for the public (e.g., schools); (3) becoming a member of the village council.

Bone Regency is one of the leading rice-producing districts in South Sulawesi Province, Indonesia. Since the early 2010s, perceptions of ecological diversity have driven conservation actions to maintain village livelihoods. Local governments have developed natural resource management in collaboration with communities, including zoning schemes that divide community areas into use and conservation areas (excluding foraging activities) and prohibitions on forest destruction and fishing with dynamite or poison. This policy aims to save animals and help regenerate specific native flora and fauna (So, 2014).

Method

Between March-June 2022, data was collected using participatory approaches. Discussion groups (FGDs) focused on (1) local livelihoods, (2) nutrition, and (3) strategies to address food insecurity (Krasny et al., 2014). During the FGD discussions focused on livelihoods, the discussion participants shared their living conditions, economic activities, the role of household members, and the changing seasons. Participants also described the social classification of the community through local criteria. During the FGD on nutrition, participants jointly make a list of the foods they eat; this discussion provides contextual information for subsequent discussions regarding food limitations and strategies to overcome them.

Discussion use coping methods (Maxwell et al., 2008), participants focused on the specific circumstances that limited food availability and the approaches families used to deal with

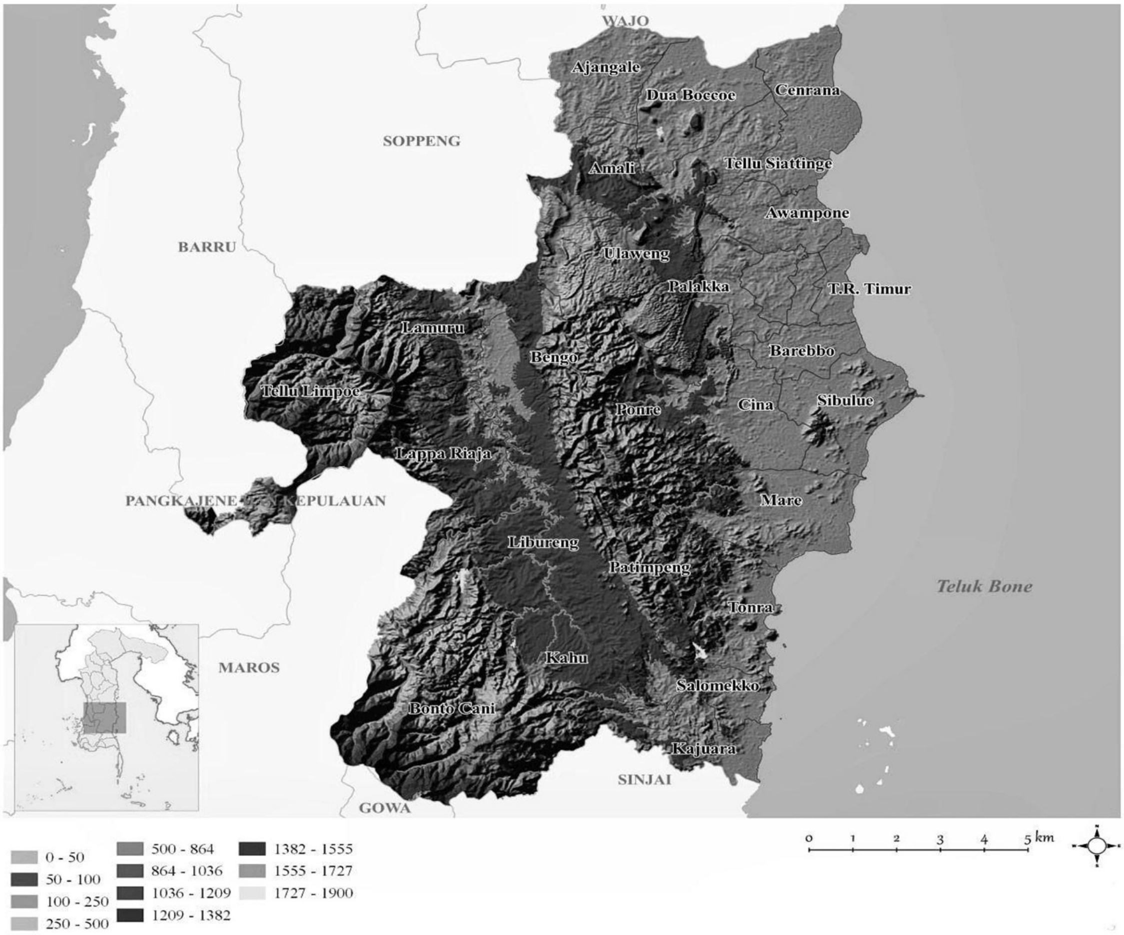

FIGURE 1
Bone Regency, Indonesia.

them. Food deprivation conditions are categorized in "severity scenarios,' which indicate how much household eating patterns are affected. This helps determine which set of coping methods is more commonly used according to varying degrees of a deteriorating situation. Finally, participants detailed the assets mobilized for every coping behavior and the formal norms influencing its implementation.

Fifteen villages contributed to this research, fourteen were interviewed individually, and the rest were grouped into two groups because they have the same livelihood and access to forest and littoral areas. Fifteen participated in the Forum Group Discussion (FGD) (Table 1), and all participants were chosen using a purposive method. Participants were grouped according to land ownership area and income. Livelihood discussion groups aim to get an alternative social description so that male and female residents of various ages are also invited to participate. Meanwhile, the nutrition discussion only involved women charged with preparing food for their families. Because one participant village considered everyone equally good, only one group discussion on coping strategies was conducted. Coping strategies are carried out separately with the "rich" and "poor" populations as a variable of susceptibility to food security (Horta et al., 2013).

One facilitator conducts a discussion group in Indonesian. When required, the fieldwork coordinator aids with the translation into local languages. Discussions were recorded, and freehand notes were collected. Contribution is optional, and written consent is collected from each person after explaining the study goals, participant rights, and data usage. The study obtained ethics approval from Sekolah Tinggi Ilmu Administrasi Puangrimaggalatung Ethics Committee.

Handwritten notes and transcribed citations were analyzed using thematic framework analysis (TFA). Food shortage scenarios and coping techniques were identified as the two main topics. According to the severity situations, the first category has three subcategories (Table 2). There are 14 subcategories in the

TABLE 1 Quantity of discussion groups and sources per topic.

Practice	Group discussion	Total duration (minutes)	Informants	
			Men	Women
Livelihoods	2	120	14	5
Native Nutrition	5	90	2	16
Adaptive methods	8	120	12	10

TABLE 2 Situations of food scarcity reported by socioeconomic aspects.

Scarcity Occasion	Group Discussions			Total
	Rich	Poor	Mixed*	
Seasonal reversal	4	4	2	10
Labor deficits in the home	4	6	2	12
Health crises	6	6	2	14

*A single discussion group in a village found that everyone there had the same income level.

second topic for each of the coping strategies that were found. Some subcategories are directly connected to the livelihood's framework: (financial, physical, social, cultural, and natural).

Capital mobilization patterns were identified by grouping coping techniques into categories based on their relevance to various severity situations; consensus ranking was applied (Maxwell et al., 2008). The approach is tailored to the severity scenario; if a strategy is tailored to both situations equally, the number of references in the adjacent category is utilized to establish the final categorization (Table 3).

Result

Native nutrition

Informants consider food filling and nutritious if it consists of rice, fish or meat, eggs, tomatoes, chilies, and stir-fried spinach. And drinks from fruit ingredients, such as oranges, apples, dragon fruit, and avocados. The main agricultural contribution to local food is rice, usually cultivated in the lowlands, and maize, available throughout the season. Residents stated that tomatoes, chilies, spinach, and long beans are typically grown in the house's yard. In contrast, fruit crops, such as chayote, lettuce, cocoa, sweet potatoes, and cassava, are usually produced in the highlands.

The contribution of natural food for the lowlands, which is often consumed, is fish, while for the highlands, it is corn. The fish captured for household use differ from those sold for commerce, such as milkfish. Most lowlanders fish for smaller species such as tuna, skipjack, anchovies, snapper, and mackerel. At the same time, food for the highlands is usually from vegetables such as corn, cassava, sweet potatoes, and pumpkin. Season affects the availability of wild food. Residents report more varieties of fish and maize during the rainy season when high water levels are thought to attract fish and crops to thrive, making farming and fishing easier.

Fishing and foraging for the lowlands (collectively known as fishermen), while farming and foraging (collectively known as farmers) are usually carried out daily. Besides corn, food is rarely stored due to humid climatic conditions for highlanders and residents' preference for fresh produce. Processed food products that are easy to store, such as instant noodles (*indomie*) and pasta, are sometimes added to food; the smoking technique of fish is used more as a culinary option.

Food scarcity

Participants consisted of two discussion groups: the "rich" community and the "poor" group. The results of the FGDs illustrate that there have been no cases of hunger in recent years, and there is always something to eat every day in the community. But the discussion results recognized several factors that affect the community's ability to obtain food in the desired proportion, diversity, or value (Table 2).

First, participants informed that for fishers, going to the sea to catch fish is spontaneous activity; although, in general, fishers manage to get fish to eat, it is not sure what kind of fish they will get every day. This uncertainty is considered more acute if the weather conditions are not good. Seasonal events (strong winds and heavy rains) usually occur in April, limiting fishing mobility. As in the rainy season, many fish species will be scattered on the edge of the sea or river. And for the highlands, vegetables and fruits will be fertile. During the transition from the rainy to the dry season, households whose livelihoods as farmers are negatively affected by the decline in agricultural yields; for fishers who catch fish in rivers, there is a decrease in river water, so the fish will also decrease. These difficulties were worsened by extremely dry or rainy seasons.

The second factor that affects food availability is the unavailability of household labor for the short term due to travel or illness; it interferes with farming and fishing activities for the family's daily needs. The last factor is a health emergency, especially one that requires hospitalization so that households will experience long and medium-term household labor unavailability; this will impact production effectiveness and financial pressure and cover travel and subsistence costs if seeking treatment in the city.

Based on the discussion, the participants described several scenarios related to the increasing condition of food insecurity. All group participants proposed a severity gradient of up to three levels, which was later adopted: (1) mild severity: short-term problems for meeting animal protein, when people find it challenging to fulfill fish or eggs for several days due to unsuccessful farming or fishing, weather effects, or the

TABLE 3 Allocation of coping methods by socioeconomic aspect and severity scenario.

Coping Strategies (CS)	Total	List of groups reporting CS to a socioeconomic aspect			List of groups reporting CS to a severity scenario			Consensus ranking
		Rich	Poor	Mixed*	Low	Medium	High	
Consuming wild foods that aren't as popular	15	3	10	2	9	5	1	Low intensity
Limiting meal servings	8	1	6	1	4	2	2	
Consuming the same foods every day (no meat or fish)	9	2	7	–	7	1	1	
Exploring seldom-visited fishing locations	11	4	6	1	2	8	0	Medium intensity
Heavy reliance on food that is given from nearby neighbors	10	1	7	2	3	6	1	
Women and children doing farming activities	8	1	6	1	2	5	1	
Agricultural profit-sharing system	11	4	5	2	2	9	0	
Relatives' financial contributions	10	2	6	2	0	1	9	High intensity
Borrow money from the bank or grocers	10	2	4	4	1	3	6	
Farming in a conservation area	10	1	8	1	1	2	7	

*A single discussion group in a village found that everyone there had the same income level.

temporary absence of domestic workers; (2) moderate severity: a more extended period of animal nutrition intake when diets are more dependent on agricultural process. This relates to weather conditions such as heavy rains or droughts and labor unavailability for a week or several days; (3) high severity: a period when families can no longer meet their nutrition needs through farming or fishing, usually because of a health crisis. These conditions lead to poor eating patterns, considering that the capacity of households to buy food is limited due to finances and medical expenses, especially if they travel to the city for health care.

Local approaches to food security improvement

Participants provide details of their opinions on food insecurity scenarios in Table 3. The "rich" and "poor" groups almost all responded similarly to coping strategies. Common coping behaviors include consuming less popular wild foods, limiting portions, and eating the same foods daily (no fish or meat). One way to avoid poverty, such as selling assets, is only mentioned once and is therefore excluded from the discussion. The only difference observed between participants for the socio-economic group in the form of dependency that seemed to be greater among the "poor" people was the profit-sharing system for the rice fields owners.

Low levels of food scarcity were associated with a response concentrating on managing local resources. This requires additional effort and energy in fishing and farming activities, which adopt rationing strategies and access to food sources. Allotment involves reducing food portion sizes or growing wild food consumption less desirable because of their flavors, such as eating eels, grasshoppers, and paddy birds. In addition, eat the same food source every day, consisting of corn, sweet potatoes, taro, and sago (without meat or fish) for several days until farming and fishing activities can resume.

Medium food severity relates to a strategy of shifting to the environment by adopting measures of nature exploration, collective consumption, mobilization of additional household resources, and a profit-sharing system. The natural exploration is carried out due to weather factors so that the affected people travel further than usual to catch fish; collective consumption depends on sharing food from neighbors or family; additional resource mobilization involves women and children in agricultural activities; undertaking a form of "profit sharing" of agricultural produce, in which households provide agricultural land to neighbors who then share the harvest or trade agricultural produce with grocers.

Responses to food insecurity of high severity focus on access to cash income, taking credit, and exploring protected areas. Increased access to cash is primarily met by unconditional financial assistance from families or selling fish catch or forest products in urban markets. To get wild vegetables or fruit, people sometimes enter conservation areas, where there are usually a lot of vegetables or fruit stocks. Sometimes it is also necessary for the community to take credit with the collateral being livestock, such as cows, to meet their daily needs.

Coping mechanisms and methods of capital utilization

In food scarcity of low intensity, local comments focus on humans as contributing to access to protein sources (Tables 4–6). The form of human capital in a healthy family member leads to access to food consumption provided by nature; the participants focus on the role of knowledge and skills possessed. This relates

TABLE 4 Addressing food insecurity with low intensity.

Coping Strategies	Types of capital						Norms
	Physical	Economic	Human	Cultural	Organic	Social	
Low intensity							
Consuming wild foods that aren't as popular	Harvest instruments		• Normal adults • Healthy adolescents	• Knowing recipes • An analysis of plant species • Foraging abilities	• Vegetables available • Fruits available	Consuming wild foods that aren't as popular	
Limiting meal servings	Harvest instruments		Normal adults	Processing knowledge of fruits and vegetables	Fertile farmland		Traditional land
Consuming the same foods every day (no meat or fish)	Equipment for processing crops		Healthy adolescents				

to the ability to identify edible plants or fruits that are not harmful to health and the habit of regulating food patterns daily so that you don't overeat. At this stage, culinary skills and recipes adapted to available ingredients, such as corn products, are the main thing, as well as growing fruits that do not need labor-intensive harvesting.

At the level of intermediate needs, households apply human, cultural, and social capital. Human capital in healthy household members leads to more vigorous efforts to access agricultural land to forest areas or catch fish in places that have never been visited, thus requiring physical capital such as spears or nets. Furthermore, the informants believe it is essential to have a strong awareness of spiritual values to avoid disturbing sacred sites when farming or fishing. In turn, social capital helps residents access crops and fruits through food-sharing behaviors rooted in traditional patterns of reciprocity as an expression of the bonds and closeness of the village community. This practice of sharing assistance does not require reciprocity on a specific timeframe or comparable exchange. This donation may be repaid at an indeterminate time in the future and other forms. Due to the lack of available labor, households sometimes mobilize women and children in farming and fishing activities. For fishing involvement, women and children are generally considered less understanding due to limited abilities and physical power compared to male fishers. The "rich" households provide agricultural land to the "poor" households so that they will share the results after harvesting. The period for managing this agricultural land varies according to the agreement between the parties.

The variety of equipment, knowledge, and abilities necessary at the most significant degree of necessity for farming or fishing is more limited than in the previous scenario because farming or fishing is aimed explicitly at observing market conditions. Social capital is also vital against severe shocks; establishing good relations with traders is very useful for commercializing crops or marine products. In addition, having family who lives in urban areas will make it easier to help financially for households experiencing health emergencies. Financial capital emerged as a factor to consider while gaining money in the form of credit at the bank, such as fulfilling the needs of agriculture or fishers. Although both "rich" and "poor" informants said they could get credit, the amount of credit that could be obtained depended on the value of their cattle. As for the monthly income in securing credit, only those with a fixed wage (village officials) can meet their food needs with this approach. In all these transactions, social capital is relevant but in the form of acquaintances with individuals who are not community members. This is different from a community-based, mutually supportive relationship; cooperation with external parties requires an agreement for payment.

Adaptation methods at the interaction of societies

Villagers' responses to different levels of food insecurity require engaging in other normative structures; in undergoing low food scarcity, the form of coping leads to community-based rules. The existence of dependence on agricultural products for daily food needs shows the importance of residents' rights to agricultural land. According to research observations, residents always have something to eat, regardless of wealth, they own at least one piece of land, and annual cultivation activities

TABLE 5 Addressing food insecurity with medium intensity.

Coping Strategies	Types of capital						Norms
	Physical	Economic	Human	Cultural	Organic	Social	
Medium intensity							
Exploring seldom-visited fishing locations	• Fishing equipment • Farming equipment • Travel gear		Normal adult male	• Knowledge of the terrain • Knowledge of fruits and vegetables • Farming or fishing skills	Vegetables, fruits, and fish are available.		• Community land rights • Gender roles • Community natural-resource management strategies
Heavy reliance on food that is given from nearby neighbors				Knowledge of reciprocity and sharing customs		A good relationship with family/ neighbors	Traditions of redistribution and reciprocity
Women and children doing farming activities	• Fishing tools • Harvest equipment		• Normal adults • Healthy adolescents	• Knowing recipes • Knowing fishing areas • Basic fishing techniques • Foraging abilities	• Fish available • Vegetables and fruits available		• Community land rights • Gender roles • Community natural-resource management strategies
Agricultural profit-sharing system	• Tackle for fishing • Tools for agriculture					A good relationship with neighbors/ family	• Gender roles • Equal profit-sharing rules

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TABLE 6 Addressing food insecurity with high intensity.

Coping Strategies	Types of capital						Norms
	Physical	Economic	Human	Cultural	Organic	Social	
High intensity							
Relatives' financial contributions						• Significant connections with family • Cities with relatives	
Borrow money from the bank or grocers		Cash inflow				Excellent rapport with banks or grocers	Business rules
Farming in a conservation area	• Farming tools • Travel tools		Adults in good health: male or female	• Knowledge of where to farm • Farming skills	Land available		• Community land rights • Community administration structures • Market rules

provide immediate access to food, despite the constant nature of foraging practices.

With medium food insecurity, residents are exposed to a mix of local and external regulations. This includes the right of residents to exploit natural resources in their territory and the obligation to respect conservation areas. In addition, the tradition of sharing food with relatives or neighbors; harvest-sharing mechanisms, however, are highly dependent on the market economy. In the market, there is competition among people because they offer the same crops (vegetables, fruits, or fish). Meanwhile, seasonal effects on traditional products to market transactions sometimes create low market prices. Market prices are currently influenced by external factors, such as fluctuations in cooking oil and fuel prices.

This mix of local and global standards is also observed at high levels of food insufficiency. In times of severity following a health emergency, communities depend on agricultural land for essential food sources and exploitation rights in marine areas or forests to obtain vegetables, fruit, or fish to sell. If exploitation is carried out in a conservation area, communication with the village government is required; residents then convey the nature of the emergency and how many resources are needed. If vegetables, fruit, or fish are obtained, villagers face challenges in market economic conditions. The informant explained that selling vegetables, fruit, or fish is difficult to get high profits due to the presence of grocers and the market situation. Village markets are usually purchased by grocers at low prices, while transportation costs to the city are relatively high for urban markets. The informant's explanation of the "greedy" traders illustrates the villagers' obstacles in overcoming these problems.

Discussion

The explanation of diet, food security, and behavior in dealing with problems in Bone Regency focuses on three things from the socio-economic adaptive of food security in subsistence societies in Indonesia. First, similar to the results of research on nutrition in the socio-ecological environment, villagers have adapted to meet their daily needs through biodiversity, with natural food being the central part of residents' nutritional intake (Sunderland et al., 2013). However, dependence on raw food exposes citizens to constant fluctuations in access to food. Denial activity is inherently difficult to predict and does not guarantee stable access to quality nutrient intake, even though fishers and farmers have substantive skills and work in favorable climatic conditions. Villagers are also vulnerable to bad climates, such as floods or prolonged droughts, thereby reducing the availability of food from nature and directly limiting people's physical access to farming or fishing. Traditional livelihood activities are also vulnerable to the unavailability of labor in households. Given that farming or fishing activities are carried out every day, the unavailability of work due to illness will rapidly impact the fulfillment of food in the household. Health conditions can potentially interfere with the household's ability to meet daily needs if they have bodily disabilities or chronic illnesses. The role of adult men in the household is the main thing; apart from being the head of the household, they are also responsible for agricultural or fishing activities.

Second, there is no indication that poor weather conditions, labor shortages, or health issues are creating hunger or poverty in the area, showing that regional food sources are robust enough to prevent acute food insufficiency (Diamond-Smith et al., 2019). While sharing food from family or neighbors becomes a mitigation measure if there is food insecurity in the medium term in Bone Regency, regular access to nutrition is mostly fulfilled through culturally entrenched community norms that support agricultural land management or fishing. The local wisdom system, intercropping seasonal crops, cultivating crops such as corn in the highlands, gardening in the yard, and ensuring a visit to staple crops throughout the year. During the same period, the agricultural production-sharing system allows residents to farm regardless of their wealth. Previous research has focused on the role of forest resources in insurance mechanisms (Paumgarten and Shackleton, 2011). The results of our study illustrate that for the same socio-economic part, forest and marine products have a role for villagers during food insecurity. This means that forest and aquatic products help provide nutrition for villagers dependent on agricultural and fishing activities through the availability of alternative protein sources (e.g., vegetables or fruits) and cash sources (fish) to buy processed foods that are easy and durable if stored. In addition, although sales of forest or marine products are usually low in the market because it depends on the market situation, as reported in the results of this study and elsewhere (Vliet et al., 2014), it is a practical method to deal with food insufficiency, because most of the villagers have been able to fulfill the most basic needs through agricultural products or fishers.

Third, as stated by the informant, villagers' response to the threat of food insecurity illustrates a sturdy dependence on ecological capital (Paumgarten et al., 2018). How to use it varies according to the level of food insecurity. At a low level of food insecurity, villagers can use a variety of natural foods to create food security. This limited choice illustrates a gradual change in the types of food fulfillment activities by villagers, namely shifting from non-monetary collective consumption to the trade sector. Under heavy pressure, villagers focus on the exchange rate of natural resources as products. As for the prevention of severe food insecurity, the informant explained that it might not be seen as a form of poverty but only described as a failure in the capacity for local livelihoods to meet household food needs. Villagers were forced to move away from their community life into a broad economic activity. For villagers, this is a big challenge because of the transition. Apart from being small economic actors, villagers rarely communicate with city traders and have minimal knowledge of market situations.

Fourth, from several levels of village food insecurity, this situation helps to identify sustainability challenges related to natural ecosystems and subsistence villagers' food security. Although local adaptation to the environment and forest or marine conditions is well maintained to create food security in Bone Regency, it is questionable if food stability will become periodic access to the fulfillment of sufficient nutritious food for healthy living and expected growth (preventing stunting) (FAO, 2017). Of course, research on nutrition shows that traditional food methods can provide a balanced and healthy diet (Kuhnlein et al., 2013). Fluctuations in the quantity and quality of food villagers consume, such as labor shortages and climatic conditions, are common. Historical meteorological data show frequent above-average droughts and floods (Runtunuwu et al., 2011). For example, a 2015 study in Batu City, Malang Province, found that farmers reported stopping agricultural activities during the dry season (Chiari, 2015). At the same time, the lifestyle of subsistence farmers who live in forest areas has increased for energy needs. Research in the Amazon region noted that subsistence means of support provide daily energy needs among 3,200 and 5,900 cal, closely related to seasonal situations (Duran et al., 2016). A temporary inability to meet the caloric intake is likely to impact villagers' health, especially for vulnerable groups such as pregnant and lactating women and toddlers (Burchi et al., 2011).

The design of prospective environmental dynamics raises additional concerns. To date, biodiversity in Bone District has been observed to support alterations in food availability such that times of food insecurity are short-term, and some of the less desirable natural foods are usually available when preferred alternatives are not available. Nevertheless, the local ecological balance could be due to the influence of environmental changes on a grander scale (Pramova et al., 2012). For example, climatological evaluations for parts of Indonesia have noted intensification and potential for drought in the dry season (Dewi, 2019), and data from conservation models show areas rich in biodiversity can overcome threats of severity originating in other regions due to the continued impact of deforestation (Ataur Rahman and Rahman, 2015).

The dependence test of natural capital with other capital produces significance based on the population's capacity to utilize the existing ecosystem. Human capital has a significant role considering that a healthy workforce can only manage natural resources in a subsistence economy. In Indonesia, villagers confront health hazards such as a lack of sanitary infrastructure, restricted access to health care, and living in places where widespread tropical illnesses such as dengue fever (Wulandari, 2016). Uncertainty about the effect of climate change on vector-borne diseases (Brondízio et al., 2016) emphasizes the need to include human capital issues in conservation arguments over food security. Village peoples' food security may be jeopardized not just by repeated short-term labor losses but also by the potential for minor diseases to become health crises owing to a lack of care. Furthermore, endemic disorders might impair people's ability to absorb nutrients from meals (Sabagh et al., 2021).

Food insecurity is severe, yet a significant amount of money emerges as communities are compelled to seek resources in non-community. Cultural assessment and social capital work together as primary natural resource mediators. The style of communal eating that has become the villagers' local wisdom enables them to get food from relatives or neighbors (Kuhnlein et al., 2013). Similarly, environmental knowledge and the ability of communities to cultivate the land are essential for ensuring access to natural food (Paumgarten and Shackleton, 2011). Discussions discuss nature-based techniques that assist villages outside the local setting, where typically, the emphasis has been on the household-level economy (Ekici and Besim, 2016) or measurements of personal nutrition (Piperata et al., 2011). With this community-based support, there are apparent limits since the resources required to meet the nutritional needs of villages may not be accessible locally. For these conditions, networking with outside individuals as social capital becomes a link for offerings to villagers dealing with food insecurity (Bebbington et al., 2006). Link to external resources also shows that it has a vital role in increasing the cultural capital of villagers. Minimal market data access is an economic obstacle that affects market-oriented agriculture or marine products and subsistence households experiencing food insecurity (Vliet et al., 2014).

Some hierarchical obstacles raised concerns about the function of marine or forest components in making appropriate contributions to subsistence-oriented villages experiencing acute food insecurity. Furthermore, villagers' adaptability to the environment supports long-term capital, the value of which is restricted in the market system. The expression of human capital focuses on physical strength, and this physical capital comprises agricultural or fishing equipment (Almendarez, 2013). The qualities that allow a family to follow traditional livelihoods effectively disadvantage it in the larger political economy (Rigg, 2007). Furthermore, physical isolation to protect communities from biological diversity loss often promotes worsening market circumstances for unfavorable bargains (Vliet et al., 2014). This research shows that farmers and fishers are obliged to compete, transportation expenses are considerable, and merchants have pricing control. These obstacles erode environmental sustainability and nature-based nutrition insurance schemes. Furthermore, continual environmental changes harm livelihoods, putting additional strain on crops such as vegetables and fruits as locals resort to the vegetable or fruit commerce to supplement their earnings (Vliet et al., 2014).

Our findings on capital assets have possible implications for global and national policies. Many policies focus on strengthening the agricultural sector by increasing export-oriented production, focusing primarily on commodity crops; these initiatives often ignore pressing local needs, focusing on indirect benefits from ecosystems (Daw et al., 2011), and often unintentionally cause environmental damage. In the rural landscapes we studied, outcomes for food security were linked to biodiversity in terms of ready access to land for local people and human capital. In food security, the main themes considered include social, human, and natural capital; for example, food production depends on natural capital, requires health and knowledge, and often benefits from good social relationships with others (Wittman et al., 2017). These findings indicate that natural resource wealth and human capital influence food security in Bone Regency. It, therefore, seems essential to encourage synergies between food security and biodiversity conservation. As identified in this study, strategies appropriate for specific rural areas must be complemented by strategies tailored to urban areas and possible interactions between different landscapes. For example, in many developing countries, rapid urbanization uses resources generated in rural and suburban areas (Lerner and Eakin, 2011), thereby creating connections between different landscapes. Long-distance relationships between landscapes can also be meaningful. Our findings on the role of human capital and the environment demonstrate the relevance of interactions with places outside a particular landscape *via* socio-ecological (Liu et al., 2013).

Limitations

There are several barriers to using the participative technique in this investigation. First, while the study team has incorporated several sources, the informants do not constitute a statistically representative sample. This research examines socioeconomic situations and consistently delivers conclusions based on the discussion group and interview data. As a result, it is questionable if this concealed bias could influence informants (Mosse, 1994), limiting the study's generalizability to specific locations.

This research approach does not use strategies for dealing with food emergencies, like as calorie restriction or stunting (FAO, 2017). We explore the exact dimensions of food security that the informants have directly experienced and grasped since the participatory method stresses local representation and knowledge (Schreckenberg et al., 2016). This qualitative study's findings reveal a link between nature and people, which may be utilized as data for future quantitative research on food security. Furthermore, the results of this study give information that may be used to better understand villagers' policy decisions about nutrient intake and resource protection (Kuhnlein et al., 2013).

Because participatory research attempts to explain real situations in a limited amount of time (Mosse, 1994), its limitation is that it does not analyze in-depth knowledge and perception as a social method. Furthermore, concentrating on people's experiences restricts our understanding of the link to outside variables. The resilience report will give preliminary data on complicated and dynamic phenomena, allowing the long-term study to expand knowledge. Future studies will add to firsthand monitoring of villagers' interactions outside the community.

Conclusion

This research examines the role of natural resources in ensuring food security for Indonesian villages. The study's results illustrate how ecosystems do not offer enough protection owing to fluctuating climates, difficulties anticipating farming and fishing activities, and significant food insecurity for families due to labor loss. Furthermore, solutions for substantial food insecurity are implemented outside local socio-ecological conditions, which might harm communities. Moreover, villagers are hesitant to employ tactics not in line with their livelihoods since previous experiences have resulted in the loss of culture and biodiversity (Kuhnlein et al., 2013).

Our findings suggest that the prevailing view of the relationship between food security and natural resources can trigger self-fulfilling prophecies. We see an urgent need to bring social system characteristics back into existing discourses on food security and nature conservation—including issues related to equity, social capital, and people (Sunderland, 2011; Zimmerer, 2013). To this end, a socio-ecological systems perspective can provide a helpful way forward. Thus, further research is required to investigate the socio-ecological impact of food security in various combinations of market integration and attempts to exploit natural resources (Poppy et al., 2014). The evaluation is based on more than just environmental factors, dietary intake, and economics. Social structures that enable natural resource cooperation for local food supply and promote the resilience of traditional ecosystems should be evaluated appropriately. Thus, examining people's understanding of food security is necessary for future policy implementation.

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.

Ethics statement

The study obtained ethics approval from Sekolah Tinggi Ilmu Administrasi Puangrimaggalatung Ethics Committee. Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

Author contributions

YY planning and developing methods in studies and research in Bone Regency, the drafting of articles until the submission process, collecting data, and conducting interviews. AC helping analyze the findings, helping draft articles, participate in making observations and help analyze the results, provide input and participate in compiling and improving the writing, help process data, and perform similarity analysis in articles. Both authors contributed to the report and approved the submitted version.

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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.

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Enhancing the resilience of food production systems for food and nutritional security under climate change in Nepal

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Background: Climate change in Nepal has posed a considerable challenge to agricultural productivity and has threatened food and nutritional security at multiple levels. This study aims to assess the impacts of climate change on national food production and food and nutritional security as well as document issue-based prioritized adaptation options for a resilient food production system.

Methods: This study considers temperature, precipitation, and their anomalies as the key factors affecting food production in Nepal. Nationwide precipitation trends along with their association with the annual production of major cereal crops in Nepal were assessed using data from the last three decades (1990–2018). The annual productions of the major cereal crops were summed and normalized to calculate production index scores in the districts. Scores were plotted and visualized into maps using the R programming. In three ecological regions, the distribution of flood and extreme rainfall events and cases of malnutrition from 2005 to 2018 were plotted. The effects of climate change and highest priority adaptation options at the district level were documented through a review of national policies and literature studies and qualitative research based on Focus Group Discussions (FGDs).

Results: Between 1990 and 2018, the overall average production of major cereal crops in Nepal was increased by around 2,245 MT annually. In the district level index analysis, the highest production score was found for Jhapa and Morang while the lowest production score was found for Humla. Cases of malnutrition in some districts coincided with flood and heavy rainfall events, indicating that climate change and extreme climatic events have a role to play in food production and security. Growing drought-tolerant crops, changes in crop cycle, riverbed farming practices, and development of short-term strategies, such as contingency crop planning, changing plantation dates, plantation of short-duration varieties, and evacuation schemes. Similarly, long-term strategies, such as encouraging out-migration of population to safer locations, resettlement programs with transformative livelihood options, and sustainable agricultural practices were found to be key prioritized adaptation measures for a resilient food system.

Conclusion: In Nepal, climate change and the increasing frequency and magnitude of extreme climatic events adversely affect the food production system, which has become a serious threat to food and nutritional security. The implementation of evidence-based practices to build a resilient food system specific to climate-vulnerable hotspots at the district and local levels is the nation's current need.

KEYWORDS

adaptation, climate change, food security, malnutrition, nutrition, resilient

Introduction

Globally, climate change is one of the greatest threats to agriculture, food security, and human health (Gregory et al., 2005; Schnitter and Berry, 2019). Nepal is highly vulnerable to climate change. The impacts of climate change are alarming due to the country's diverse topography and corresponding climatic variations, natural resource-based livelihoods, and resource constraints to adapt to the increasing occurrence of extreme climatic events, hazards, and disasters (Rasul et al., 2020). Agriculture is one of the major sources of income and livelihood for around 60% of Nepalese households, most of which follow traditional cultivation practices and rely on monsoon rains. Fluctuations in rainfall patterns adversely affect crop production and food insecurity, leading to nutritional insecurity. Water-related threats, such as floods and droughts, account for almost 70% of all economic losses in mountainous countries like Nepal (Eriksson et al., 2009; Shrestha et al., 2010). Climate change affects agriculture, livestock, water and forest resources and, consequently has an impact on long-term food security (Rasul, 2021).

The concept of food and nutritional security is complex and multidimensional in nature. The Food and Agricultural Organization unpacks food security into availability, accessibility, utilization, and stability (FAO, 2005). Even though all these conditions are important elements for food and nutritional security, the availability of sufficient food and its accessibility by different groups of people are the foremost necessary conditions for food security, without which other elements cannot be fulfilled (Nepal and Neupane, 2022). The impact of climate change and extreme events is more pronounced on the above two pillars of food security, namely, food availability and accessibility.

The effects of droughts on agriculture and food security have significant consequences on the long-term development of a country where agriculture is a prime source of the national economy. Food security in developing countries like Nepal is mostly jeopardized by trade, population growth, climate change, deforestation, and desertification (Malla, 2008; Thakur, 2017). Climate change mainly affects two aspects of food and nutritional security such as food availability and access. Farms face droughts and increased crop diseases and pests, and frequent climate-related disasters that affect agricultural yields. The impacts of climate change are expected to reduce food production, resulting in decreased global food supply and increased food prices, making food inaccessible to poor communities. Farmers are heavily affected by climate change, which puts enormous pressure on the nation to achieve its sustainable development goal related to food and nutritional security indicators.

In Nepal, a higher proportion of agricultural land is rainfed. Climate change is expected to impact the water cycle, rainfall pattern, timing, and intensity of the rainfall, resulting in a change in production. An increase in the occurrence of climatic hazards, such as floods and heavy rain, damages cultivated crops, reduces food production and causes food insecurity (Atanga and Tankpa, 2021), and escalates the challenge of hunger and malnutrition (FAO, 2015; MoFE, 2021a). Certainly, a decline in food production increases the malnutrition rate and has serious consequences, especially among children and other vulnerable groups (Regmi and Adhikari, 2007). Frequent and intense droughts and floods have further reduced agricultural yields. In addition to climatic factors, practices, such as inappropriate farming, conversion of agricultural lands to housing, loss of soil fertility, erosion, land degradation, high reliance on pesticides, and youth migration, are making people more vulnerable to food insecurity (Bhatta et al., 2019). Climate change together with unsustainable anthropogenic practices has increased pressure on agricultural production, and food security has an impact on several national and international targets. This has led to an increase in food and nutritional insecurities among poor and marginalized communities, smallholders, pregnant and lactating women, mothers and children, and the elderly population who are already at risk from climatic hazards and food insecurity.

This paper aims to find out the impacts of climate change on agricultural production systems and nutritional security along with the identification, evaluation, and documentation of adaptation practices in response to climate change at multiple scales in Nepal.

Methods

Study area

Nepal is a landlocked country bordering India to the east, west, and south, and China to the north. It has a diverse geographic distribution in three ecological regions; Tarai (17%), Hill (62%), and Mountain (21%). Approximately 66% of the economically active population is engaged in agriculture, and this sector contributes to 25.8% of the nation's gross domestic product in 2020 (MoF, 2021). Rice, wheat, maize, barley, millet, and potato are considered the major crops produced in the country, contributing to more than 90% of the country's total food production (MoALD, 2021). Nepal's climate varies considerably in seasons and altitudes. There are four distinct seasons. The pre-monsoon season (March–May), is hot and dry, with scattered rainfall. The monsoon (June–September) is hot and humid, with overcast skies and intense precipitation. Rainfall is reduced during the post-monsoon (October–November) while the winter (December–February) is with clear skies, low temperatures, and little precipitation (Shrestha et al., 2019). Nepalese agriculture is heavily dependent on monsoon rain, with almost 67% of agriculture based on rainfed cultivation (Shrestha et al., 2013). Due to diversity in geography, Nepal is exposed to a range of climate risks and water-related hazards.

Data collection and analysis

We used the mixed method approach. Quantitative data were gathered from secondary sources, and qualitative data were collected from primary sources through focus group discussions (FGD). The data on malnutrition cases from 2005 to 2018 were retrieved from the Health Management Information System database of the Department of Health Services (DoHS, 2021). Annual food production parameters, production area (ha), food production (MT), and yield (kg/ha) of five major cereals (paddy, maize, wheat, barley, and millet) from 1990 to 2018 were obtained from the Ministry of Agriculture, Government of Nepal (MoALD, 2021). The annual average of precipitation (cm) of Nepal from 1990 to 2018 produced by the Climate Research Unit of the University of East Anglia, UK, presented at a 0.5 $\times$ 0.5° (50 $\times$ 50 km) was taken from the World Bank Group (World Bank, 2021). Similarly, flood and heavy rainfall events data in districts from 2005 to 2018 were collected from the Nepal Disaster Risk Reduction Portal of the Ministry of Home Affairs, the Government of Nepal (MoHA, 2022).

A descriptive analysis of the distribution of food production parameters of five major crops and annual average precipitation was performed. The occurrence of extreme climatic events vary in different districts and ecological regions of Nepal (MoFE, 2021b). Therefore, we calculated the mean value of floods and heavy rainfall in each region separately. Districts with higher than average hazard events and the top five districts with a higher number of malnutrition cases were identified in each ecological region. Hazard events and malnutrition cases at the district level of each ecological region were plotted. The sum of the annual average production in 77 districts of Nepal was normalized on a scale of 0–1 using the minimum–maximum formula. Data analysis was performed in Microsoft Excel (MS office version-10), and visualization in maps was performed using R programming (version 4.2.1).

Between February and June 2019, we performed 12 FGDs in six districts of Nepal, i.e., two FGDs in each district. The districts were selected in a way to represent the three ecological regions of Nepal, which consisted of Mountain (Sindhupalchowk and Dolakha), mid-Hill (Kavre and Ramechhap), and inner-Tarai (Chitwan and Makawanpur). Each FGD session consisted of seven participants. They were purposively selected from farming communities representing smallholders, women, and marginalized people. The discussion sessions were conducted in a community setting after acquiring farmers' consent to participate. Policy and program information was extracted from the published literature studies and policy documents and reports related to climate change and adaptation in Nepal.

Results and discussion

Cereal crop production trend

From the analysis of crop production data between 1990 and 2018, the highest and lowest average annual volumes of cereal production were found for paddy at 54,888 MT and barley at 438 MT, respectively. Average annual production was found to have increasing trends in paddy, maize, wheat, and millet. The cultivated land area for maize, wheat, and barley was almost the same during this period while it shrank and expanded in paddy and millet. During these three decades, the overall average production of five major crops in Nepal seems to have increased by 2,245 MT annually. The highest annual average increase in production was found in paddy (1,026 MT) while the lowest increase was found in barley (1.2 MT) (Figure 1).

In the regression model, the highest (95%) coefficient of determination (R^2) was found for wheat, which implied that wheat production was linear while the lowest (3%) R^2 was found for barley. In all the major cereals, a variation in the average annual production was found with the change in the average annual precipitation in the country. However, the highest fluctuation in average annual production of paddy and barley was marked by declining and rising trends in the average annual precipitation (Figure 1).

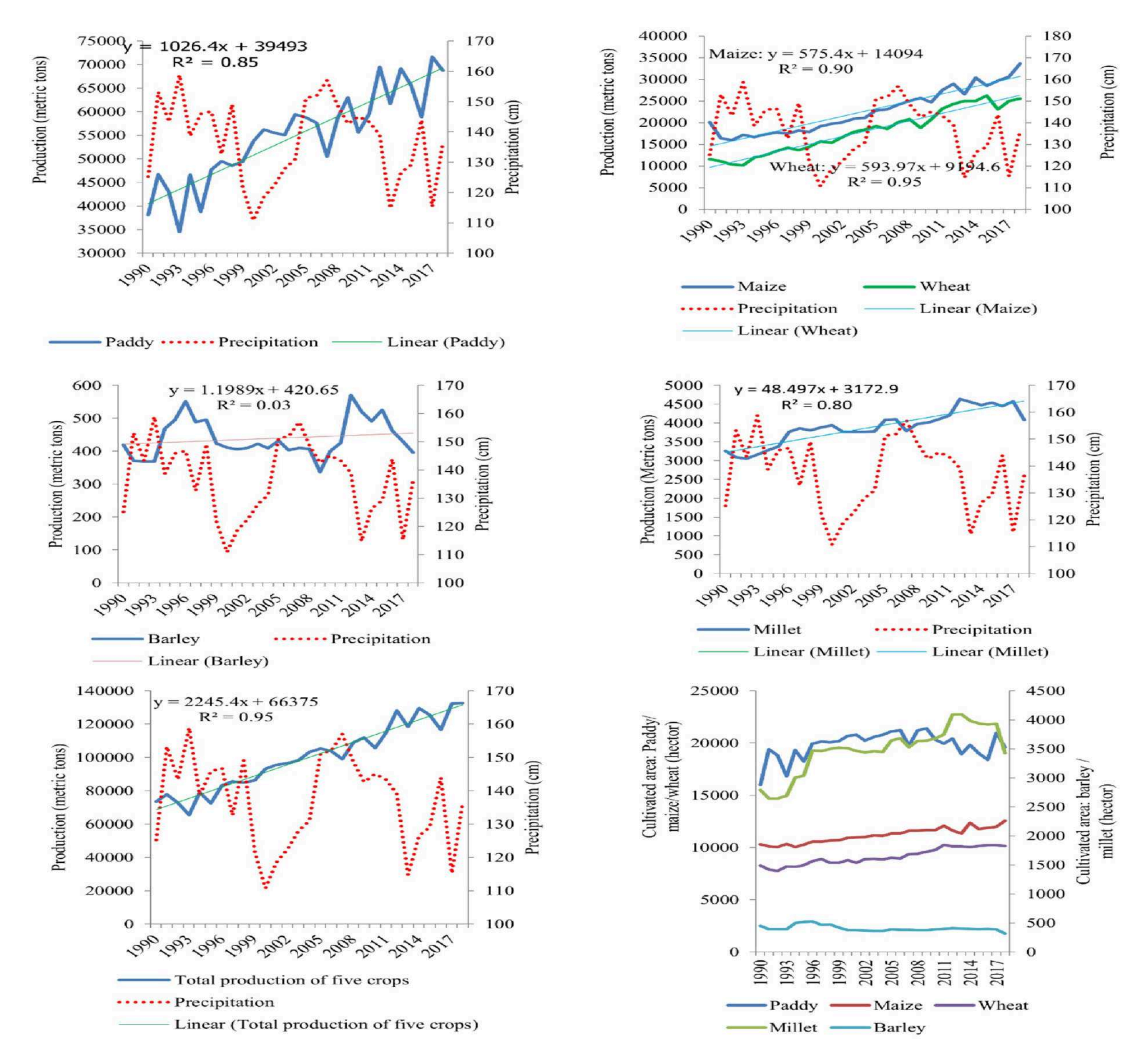

FIGURE 1
Trend of production of five major cereal crops from 1990 to 2018 vs precipitation trend.

Food production varied in the different districts of Nepal. Food production is determined by climatic factors along with non-climatic factors, such as soil quality, topography, irrigation facility, labor, technology, and the use of pesticides. In this study, index analysis at the district level shows that the highest production of the major cereal crops is found in the Bara, Morang, and Jhapa districts, while the lowest production score was found in six hill districts (Achham, Baitadi, Dadeldhura, Doti, Pyuthan, and Western Rukum) and 12 mountain districts [Bajhang, Bajura, Darchula, Dolakha, Dolpa, Kalikot, Humla, Jumla, Mugu, Mustang, Rasuwa, and Taplejung (Figure 2)]. The Food production annual average (Normalized index) for all five crops i.e. paddy, maize, wheat, barley, and millet are attached as Supplementary Figures 1–5.

Food insecurity and malnutrition under climate change

Food insecurity and malnutrition is one of the major health issues caused by climate change in Nepal, where almost 17% of the population is multidimensionally poor (NPC, 2021). Food insecurity is also associated with susceptibility to disasters, such as drought, floods, pests and diseases, and landslides, vulnerability to fluctuations in global prices, civil turmoil, disease, and poor infrastructure. In Nepal, 4.6 million people are noted to live with food insecurity, where 20% of households are reported to be mildly food insecure, 22% of households are moderately food insecure, and 10% of households are severely food insecure (Chemjong and KC, 2020).

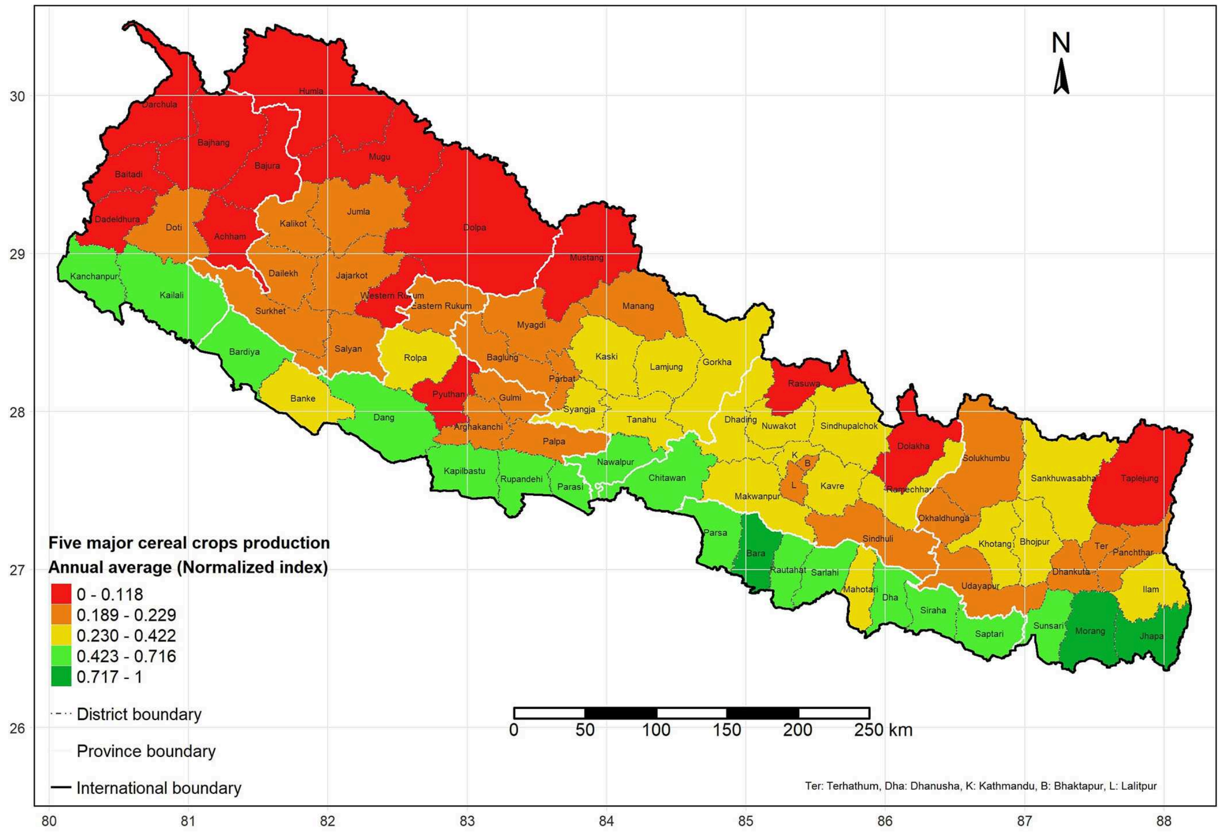

FIGURE 2
Distribution of production scores by the district of Nepal.

A rise in maximum temperature has decreased agricultural productivity, leading to an increased threat of food insecurity (Pant, 2012). In the Western and Tarai region of Nepal, many people are affected annually due to heavy rainfall, flash floods, and landslides. These disasters have a direct impact on agricultural production and food security. For instance, paddy was one of the main crops in Nepal, but it was severely affected by the prolonged drought and late monsoon (Thapa and Hussain, 2021).

Nutritional deficiency diseases, including malnutrition, are the most serious consequences of food insecurity and have a multitude of health and economic implications (Chinnakali et al., 2014). In addition to the socioeconomic factors, environmental factors, such as increased annual average precipitation, mean temperature, and drought, are linked with malnutrition cases in some districts of Nepal (MoFE, 2021b). We also noted the existence of a certain relationship between floods and extreme rainfall with malnutrition cases in most districts of three ecological regions of Nepal. Increasing the number of flood events was found to coincide with the higher number of malnutrition cases in Morang, Bajura, Kaski, and Western Rukum while increasing the incidence of heavy rainfall events coexisted with the higher number of malnutrition cases in Sarlahi, Bara, Dhading, Humla, and Jajarkot. In Rautahat and Achham, an increase in flood and heavy rainfall events was found to be somehow related with the higher number of malnutrition cases (Figure 3).

However, there are some instances where food production and malnutrition cases do not seem to coincide with floods and heavy rainfall. This could be due to humanitarian interventions in some regions (Conway et al., 2020), along with some adaptive capacity and preparedness measures adopted by farmers. Both natural and anthropogenic factors contribute to crop production, and climate change and extreme events can alter the usual trend of the overall agricultural production.

Based on the secondary data analysis, we can observe a decline trend of malnutrition cases from 2005 to 2018 in Nepal. The cases of malnutrition are decreasing in the Hill and Mountain regions while they are slightly increasing in the Tarai region. The mobilization of community health workers to increase the provision of basic health interventions, specific programs focused on child and

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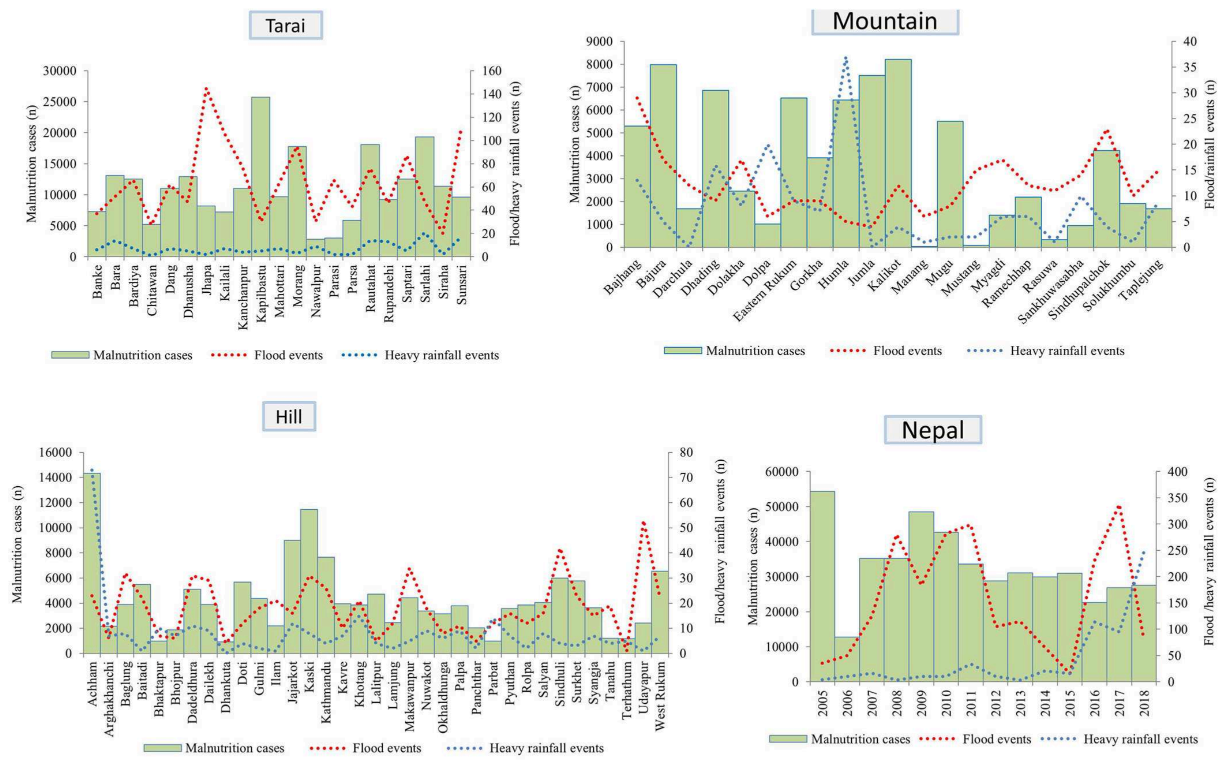

FIGURE 3
Ecological and district-wise distribution of malnutrition cases, flood, and rainfall events from 2005 to 2018 in Nepal.

maternal nutrition along with prioritized nutrition sensitive initiatives from different government and nongovernment agencies has been noted as a major driver to decline the number of malnutrition cases (Conway et al., 2020). Despite Nepal's progress in reducing malnutrition, it remains one of the major causes of child mortality (DoHS, 2021). The situation of malnutrition is alarming in the country, especially among infants, adolescent girls, and pregnant and lactating mothers (USAID, 2021). National food security has been getting high priority in each development plan in Nepal, but the situation has not improved as anticipated. Likewise, despite the country's focus on the production of adequate food supplies, food insecurity remains an alarming national problem.

Climate change has adversely affected Nepal's economy by affecting the livelihoods of those who rely heavily on agriculture. The majority of Nepalese people are subsistence farmers (MoPE, 2004). In 2006, farmers in the eastern part of the country experienced a low amount of rainfall during the monsoon season, which resulted in 10% of the land being left fallow, causing a 12.5% reduction in production. In the same year, high floods hit the western part of Nepal, reducing the production by more than 30% (Regmi and Adhikari, 2007). Nepalese communities are at high risk and prone to climate-induced disasters due to their higher exposure and poor capacity to adopt and/or respond to these climate stressors (DHM, 2017; Walker et al., 2019).

Crop production cycles have been disrupted due to climate change, which has especially impacted vulnerable groups, such as marginal farmers, indigenous groups, female-headed households (Hussain et al., 2016). From the FGD sessions, we found that the vulnerable groups are those with limited access and control over resources, which has impacted them more than the others. An increase in maladaptation, such as reduced meals, sale of assets, and girls dropping out of schools, has also been observed in Nepalese communities due to acute food insecurity (Khadka et al., 2014; Hussain et al., 2016). Similar consequences were also observed during our FGD sessions. We have observed that limited access to land and credit and lack of climate smart farming knowledge make the vulnerable farmer group less likely to change conventional farming and adopt climate-resilient farming practices to combat the impacts of climate change. Climate change has adversely affected the lifestyle, livelihoods, health status of the most vulnerable farmer groups, making them more sensitive to adapt to a changing climate (Khadka et al., 2014).

We found that frost is one of the main climate hazards for farming communities in Nepal. A number of villagers from higher altitudes noted that though there is a reduction in snowfall, there is an increased amount of frost, which severely affects vegetable production. During the time of our study, most of the potato farmers reported that they experience a reduction in their production by almost half (49%) in 2019 due to severe frosts.

Farmers also reported that all villagers have experienced an increase in their production costs as they are bound to buy expensive pesticides. Multiple diseases and pests that were normally found at lower altitudes and in warmer climatic conditions are now thriving at higher altitude, suggesting that climate change has resulted in enabling environmental conditions for such pests and diseases to thrive at higher altitudes. Farmers reported that the weeds, once managed with organic remedies and hand picking, are now almost incurable due to traditional measures that require the use of strong chemical pesticides.

The hailstone is not a new hazard in the mountainous areas of Nepal. Villagers are mostly prepared for some level of hailstones during March and May. However, we found that in the last 10 years, the intensity and frequency of hailstone have changed and go beyond the expectations and preparation of the villagers. Moreover, future scenarios analysis of extreme events shows that they are going to increase under different climate change projections i.e. Representative Concentration Pathways of 4.5 and 8.5 (MoFE, 2019). With the increase in numbers and intensity of extreme events, farmers shared their threat of significantly losing their wheat and potato production, thus impacting production and food security.

Considering the importance of land-based livelihoods in the agriculture sector of Nepal, the main impact of climate hazards is the reduction of water availability. This study shows that excess water due to extreme climatic conditions and too less water during the dry season are also affecting crop productivity. Moreover, in the future, climatic events such as extreme hot days are likely to increase by up to 55% by 2060 and up to 70% by 2090. Along with these heat waves, cold waves, heavy rainfall, and fire events are likely to increase (MoFE, 2019). Moreover with increased temperature, warm days and nights, and heat waves, it is likely that seasonal drought will also increase (Dahal et al., 2018). Currently, the majority of the hilly communities (85%) depend on rainfed agriculture (Kattel and Nepal, 2022). A similar case was observed in the districts selected for the FGDs. Irrigation systems are limited due to the hilly terrain and fragmented land holdings, on the other hand, running water sources are decreased by 30% by 2025 (Alexandratos and Bruinsma, 2012). Farmers acknowledged that many of the drinking water sources and small irrigation schemes of the hills have dried up. Therefore, extreme, unpredictable and unfavorable climatic conditions along with various anthropogenic factors are likely to have adverse impacts on agricultural production in Nepal.

In this study, villages in Dolakha district reported that in the early days, especially in the monsoon season, the rains used to stay throughout the monsoon, but recently there were several monsoon breaks. The pattern of too much and too little rainfall is increasing. There is often a shortage of winter rains, which has resulted in reduced productivity of wheat and other winter crops. Farmers from Chitwan and Makwanpur districts also mentioned that they have not noticed the occurrence of winter rainfall in the last 10 years. As a result, they have stopped cultivating wheat and mustard, which were previously major crops in their area. Most of the rice growers, particularly at the tail ends of Sindhupalchowk, Dolakha and Kavre, shared an occupational disturbance from recurrent floods and droughts.

Adaptation options enhancing a resilient food production system

Based on FGDs conducted among farmers, it was noted that local communities have developed their own local adaptation practices over time, several of which have been tested and validated over time while others are evolving. Adaptation practices adopted by local communities using their local knowledge and skills can be grouped into livestock management, migration, evacuation and resettlement, alternative crop cultivation, growing drought-tolerant crops and varieties, the change in cropping patterns, and riverbed farming. The important adaption options practiced are elaborated below.

Growing drought-tolerant varieties

The impact of climate change on land-based livelihoods is visible in Nepal. Farmers reported that they are experiencing reduced agricultural yields mainly due to drought. In response to droughts, some of the farmers in our study area have started alternative drought-tolerant crops. Many farmers in the Hill region have converted their paddy fields to maize and finger millet. Some others have started growing ginger and turmeric, which are relatively more drought tolerant than paddy, maize, and millet. These are some of the self-directed local adaptation practices.

Most of the farmers expressed their willingness to look for an alternative crop if traditional paddy cultivation is not possible to grow because of limited water availability. They were eager to try drought-tolerant varieties of paddy and other similar crops. Some of the farmers in our study areas reported starting alternative crops to replace traditional cereal crops on concentrated farmland. Tomato cultivation, tea gardening, cardamom plantation, and ginger cultivation can be taken as examples. Tomato cultivation has been practiced in those areas where there is a nearby market. Farmers also suggested that tea gardening looks good for utilizing fallow land with fewer human resources for long-term benefit. However, the market is very important to get the expected benefits from tea leaves and other crops.

Changes in the cropping system

In the FGDs carried out in Sindhupalchowk and Dolakha, farmers reported that their recent cropping cycle follows wheat—finger millet—potato/maize in a 2-year span. This is mostly because in high altitude areas farmers normally produce three crops in 2 years. As an impact of climate change, the increase in temperature has resulted in an early maturation of 1–2 months of these crops. This early maturity of crops has also been reported by other studies in eastern Nepal (Chaudhary and Aryal, 2009; Chaudhary and Bawa, 2011). In this case, farmers in these area comfortably estimate that they can add one more crop in the middle, but they are quite confused on what to add and when. Only a few innovative farmers have started some changes on a trial-and-error basis but over 95% farmers are following the same traditional cropping cycle.

Changes in the cropping cycle and irrigation facilities are also interrelated. If farmers want to add one more crop in the ongoing cycle, they need to arrange irrigation because the intensity and duration of the dry period also increase. Due to limited adaptive capacity, lots of running water sources are underutilized. Such poor adaptive capacity of farmers adds to vulnerability and weakens their climate resilience. Some of the off-farm options for livelihood are already practiced in the high hills. The paper industry, tourism industry, and the cultivation of medicinal plants can be taken as examples. Likewise, many people choose to plant other traditional varieties as they are found to be better suited for harsh environmental conditions. High hill communities have started to rely on non-timber forest products. Some of these communities are practicing an organized collection by forming cooperatives through leasehold forestry groups.

Riverbed farming

In the southern part of Nepal, where there is massive deposition of sand from rivers, cultivation on sandy riverbeds and river banks has been tried out by several farmers in the Tarai region. Some farmers are successful in producing watermelon, pointed gourd, ginger, and sweet potatoes on the sandy soil where there is recurrent soil deposition from river floods. For example, in the sand deposition created by the 2008 Koshi flood, farmers in that region are practicing riverbed farming such as watermelon, pumpkin, cucumber, and pointed gourd. The use of sand-cast lands for fruit cultivation can be a coping strategy for making the best use of unusable land. Vegetable farming is highly prone to disease and pest attacks, and to price volatility that is beyond the risk-bearing capacity of poor farmers. Similarly, the use of sand-cast lands for fruit cultivation has been taken as one of the coping strategies to make the best use of unusable lands. Unlike vegetable farming, it has been used by both small and large-scale farmers for different types of fruit depending on their risk-taking potential (Rai et al., 2019). There are several other riverbed farming initiatives undertaken by different institutions (Gurung et al., 2012; Maharjan, 2017, 2020).

Migration and resettlement

Because of climate change, many glacier lakes are at risk of erupting. The latest study carried out by ICIMOD, 2020 shows there are 47 such glacial lakes in Nepal (Bajracharya et al., 2020). The possibility of glacier lake outburst floods (GLOFs) has been increasing in the mountainous areas of Nepal. There are several river valleys in Nepal, which are very productive and densely populated, such as Tumlingtar of Sankhuwasabha district, Nepalthok of Kavre district, and Manthali of Ramechhap district. There are hundreds of such highly productive river valleys in the country. With rising temperatures, it has become apparent that rivers fed by glacier lakes can flood at any time of the year and bring about devastating effects. All of these scenarios indicate that human settlements on the bank of glacier-fed rivers are not safe.

Furthermore, the river banks used to be the attraction of poor people and indigenous communities for fishing. Fluvial flooding, flash flooding, glacier lake outburst risk coupled with the anthropogenic factors, such as hydro projects, excessive harvesting, and the use of unnecessary fertilizers, and electrical fishing, the riverbed ecosystem has been disrupted compelling people to depend on riverbeds for their livelihoods to seek alternatives economic sources or even to migrate to other places.

Mountain people have taken immigration as an opportunity to earn a good remittance from foreign employment, on the other hand, they have fewer number of human resources for their agriculture and livestock at home. The number of domestic animals, the amount of compost, and human resources are directly related to agricultural production. The lower the input, the lower the outputs of agricultural products. This trend has created an overload for women and the feminization of agriculture as women are also taking on more roles in farming (UNDP, 2009; Paudel et al., 2020). In Nepal, the women labor population in agriculture has increased from 36% in 1981 to 45% in 1991 and 48.1% in 2001 and 49.8% in 2011 (Jalsrot Vikas Sanstha (JVS)/GWP Nepal, 2015). Similarly, the lack of proper irrigation, and climate induced disasters also compelled people to think of changing their settlements.

Conclusion

Climate change and its induced disasters, such as floods, heavy rains, and droughts, have caused notable impacts on Nepalese agriculture leading to food insecurity, threating nutritional wellbeing, and loss of overall economic development. The annual national average production of major crops is adversely affected by fluctuating precipitation and seasonal variations. However, farmers are minimizing the impacts of climate change and variability by changing cropping patterns, switching crop varieties, riverbed farming, and improving technology and water management practices. These practices are autonomous and are unlikely to build long-term adaptation and resilient food production systems. Therefore, there is a need for planned adaptation practices. This study suggests short- and long-term pathways for planned adaptation. In a short run, the focus should be on growing drought-tolerant crops, making changes to the crop cultivation cycle and riverbed farming practices, developing contingency crop planning, changing planting dates, planting short-duration varieties, or long-term strategies such as population migration to safer locations, resettlement programs with transformative livelihood options with sustainable agricultural practices.

This study also suggests further research to quantify the disaggregated impact of climate change on food production systems and its consequences on food and nutritional security, along with a rigorous cost-benefit analysis of each potential adaptation option including the transformative adaptation option is essential. To achieve this, this study has paved a solid foundation and provided guidance for policymakers and implementers.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: The data is acquired from the Ministry of Agriculture and Livestock Development, Government of Nepal for the research purpose which cannot be shared without permission from the Ministry. Requests to access these datasets should be directed to https://moald.gov.np/.

Ethics statement

The study uses freely available secondary data with permission. For the Focus Group Discussions approval was acquired from the respective Municipal office and informed consent was acquired from the participants.

Author contributions

NN and YPJ conceptualized the research and analyzed the data. NN conducted the FGD. NN, SP, RS, and YPJ analyzed the information and prepared the first draft. NN, SP, RS, YPJ, YR, and AC revised this manuscript. All authors reviewed the first draft, contributed to the improvement, reviewed the final draft, read, and agreed to the final version of this manuscript.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.968998/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Annual average production (mt) of Barley from 1970/71-2014/15.

SUPPLEMENTARY FIGURE 2
Annual average production (mt) of Maize from 1970/71-2014/15.

SUPPLEMENTARY FIGURE 3
Annual average production (mt) of Millet from 1970/71-2014/15.

SUPPLEMENTARY FIGURE 4
Annual average production (mt) of Wheat from 1970/71-2014/15.

SUPPLEMENTARY FIGURE 5
Annual average production (mt) of Paddy from 1970/71-2014/15.

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Corrigendum: Enhancing the resilience of food production systems for food and nutritional security under climate change in Nepal

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In the published article, there was an error in affiliation 3. Instead of "Policy Initiative Nepal (PIN), Lalitpur, Nepal," it should be "Policy Initiatives Nepal (PIN), Lalitpur, Nepal."

In the published article, the initials of author Yadav Prasad Joshi were incorrectly written as YJ. The correct initials in author contribution is YPJ.

In the published article, there was an error in the legend for Figure 1 as published. The corrected legend appears below. "Trend of production of five major cereal crops from 1990 to 2018 vs precipitation trend."

In the published article, the reference for (Food Agriculture Organization, 2008) was incorrectly written as Food and Agriculture Organization (2008). *Food Security Information for Action Practical Guides*. Rome: FAO. It should be FAO (2005). *Food Security Information for Action Practical Guide*. Rome: Food and Agriculture Organization (FAO).

In the published article, the reference for (Food Agriculture Organization, 2015) was incorrectly written as Food Agriculture Organization (2015). *Climate Change and Food Security: Risks and Responses*. Rome, Italy: Food and Agriculture Organization of the United Nations. Available online at: https://www.fao.org/3/i5188e/I5188E.pdf (accessed

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In the published article, there was an error in the tool that we used for map plotation.

A correction has been made to **Abstract**, **Method, 2.** This sentence previously stated:

"This study considers temperature, precipitation, and their anomalies as the key factors affecting food production in Nepal. Nationwide precipitation trends along with their association with the annual production of major cereal crops in Nepal were assessed using data from the last three decades (1990–2018). The annual productions of the major cereal crops were summed and normalized to calculate the production index scores in the districts. Scores were plotted and visualized into maps using the Geographical Information System. In three ecological regions, the distribution of flood and extreme rainfall events and cases of malnutrition from 2005 to 2018 were plotted. The effects of climate change and highest priority adaptation options at the district level were documented through a review of national policies and literature studies and qualitative research based on Focus Group Discussions (FGDs)."

The corrected sentence appears below:

"This study considers temperature, precipitation, and their anomalies as the key factors affecting food production in Nepal. Nationwide precipitation trends along with their association with the annual production of major cereal crops in Nepal were assessed using data from the last three decades (1990–2018). The annual productions of the major cereal crops were summed and normalized to calculate production index scores in the districts. Scores were plotted and visualized into maps using the R programming. In three ecological regions, the distribution of flood and extreme rainfall events and cases of malnutrition from 2005 to 2018 were plotted. The effects of climate change and highest priority adaptation options at the district level were documented through a review of national policies and literature studies and qualitative research based on Focus Group Discussions (FGDs)."

In the published article, there was an error. The sentence was lengthy sentence and several commas made it vague.

A correction has been made to **Abstract**, **Results**, 3. This sentence previously stated:

"Growing drought-tolerant crops, changes in crop cycle, riverbed farming practices, developing short-term strategies, such as contingency crop planning, changing planting dates, planting short duration varieties, schemes evacuation, and long-term strategies, such as encouraging out-migration of population to safer locations, resettlement programs with transformative livelihood options, and sustainable agricultural practices were found to be key prioritized adaptation measures for a resilient food production system."

The corrected sentence appears below:

"Growing drought-tolerant crops, changes in crop cycle, riverbed farming practices, and development of short-term strategies, such as contingency crop planning, changing plantation dates, plantation of short-duration varieties, and evacuation schemes. Similarly, long-term strategies, such as encouraging out-migration of population to safer locations, resettlement programs with transformative livelihood options, and sustainable agricultural practices were found to be key prioritized adaptation measures for a resilient food system."

In the published article, there was an error.

A correction has been made to **Introduction**, 1. This sentence previously stated:

"Nepal is one of the most countries vulnerable to climate change."

The corrected sentence appears below:

"Nepal is highly vulnerable to climate change."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Methods**, **Study area,** 1. This sentence previously stated:

"Nepal is a landlocked country bordering India to the east, west, and south, and China to the north. It has a diverse geographic distribution in three ecological regions; Tarai (17%), hill (62%), and mountain (21%)."

The corrected sentence appears below:

"Nepal is a landlocked country bordering India to the east, west, and south, and China to the north. It has a diverse geographic distribution in three ecological regions; Tarai (17%), Hill (62%), and Mountain (21%)."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Methods**, **Data collection and analysis,** 3. This sentence previously stated:

"The districts were selected in a way to represent the three ecological regions of Nepal, which consisted of mountain (Sindhupalchowk and Dolakha), mid-hill (Kavre and Ramechhap), and inner-Tarai (Chitwan and Makawanpur)."

The corrected sentence appears below:

"The districts were selected in a way to represent the three ecological regions of Nepal, which consisted of Mountain (Sindhupalchowk and Dolakha), mid-Hill (Kavre and Ramechhap), and inner-Tarai (Chitwan and Makawanpur)."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Results and Discussion: Cereal crop production trend**, 3.

This sentence previously stated:

"In this study, index analysis at the district level shows that the highest production of the major cereal crops is found in the Tabara, Morang, and Jhapa districts. While the lowest production score was found in six hill districts (Achham, Baitadi, Dadeldhura, Doti, Pyuthan, and Western Rukum) and 12 mountain districts [Bajhang, Bajura, Darchula, Dolakha, Dolpa, Kalikot, Humla, Jumla, Mugu, Mustang, Rasuwa, and Taplejung (Figure 2)]."

The corrected sentence appears below:

"In this study, index analysis at the district level shows that the highest production of the major cereal crops is found in the Bara, Morang, and Jhapa districts, while the lowest production score was found in six hill districts (Achham, Baitadi, Dadeldhura, Doti, Pyuthan, and Western Rukum) and 12 mountain districts [Bajhang, Bajura, Darchula, Dolakha, Dolpa, Kalikot, Humla, Jumla, Mugu, Mustang, Rasuwa, and Taplejung (Figure 2)]."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Results and Discussion, Food insecurity and malnutrition under climate change**, 5. This sentence previously stated:

"Based on the secondary data analysis, we can observe a decline trend of malnutrition cases from 2005 to 2018 in Nepal. The cases of malnutrition are decreasing in the hill and mountain region while they are slightly increasing in the Tarai region."

The corrected sentence appears below:

"Based on the secondary data analysis, we can observe a decline trend of malnutrition cases from 2005 to 2018 in Nepal. The cases of malnutrition are decreasing in the Hill and Mountain regions while they are slightly increasing in the Tarai region."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Results and Discussion, Food insecurity and malnutrition under climate change**, 13.

This sentence previously stated:

"As a result, they have stopped cultivating wheat and mustard, which are previously major crops in their area. Most of the rice growers, particularly at the tail ends of Sindupalchowk Dolkha and Kavre, shared an occupational disturbance from recurrent floods and droughts."

In the published article, there was an error. It was a grammatical error.

The corrected sentence appears below:

"As a result, they have stopped cultivating wheat and mustard, which were previously major crops in their area. Most of the rice growers, particularly at the tail ends of Sindhupalchowk, Dolakha and Kavre, shared an occupational disturbance from recurrent floods and droughts."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Results and Discussion, Growing drought-tolerant varieties**, 1.

This sentence previously stated:

"Many farmers in the hilly region have converted their paddy fields to maize and finger millet. Some others have started growing ginger and turmeric, which are relatively more drought tolerant than paddy, maize, and millet. These are some of the self-directed local adaptation practices."

The corrected sentence appears below:

"Many farmers in the Hill region have converted their paddy fields to maize and finger millet. Some others have started growing ginger and turmeric, which are relatively more drought tolerant than paddy, maize, and millet. These are some of the self-directed local adaptation practices."

In the published article, there was an error. It was an error due to incorrect abbreviation use.

A correction has been made to **Results and Discussion, Changes in the cropping system**, 1.

This sentence previously stated:

"In the FDGs carried out in Sindhupalchowk and Dholakha, farmers reported that their recent cropping cycle follows wheat—finger millet—potato/maize in a 2-year span."

The corrected sentence appears below:

"In the FGDs carried out in Sindhupalchowk and Dolakha, farmers reported that their recent cropping cycle follows wheat—finger millet—potato/maize in a 2-year span."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Results and Discussion, Migration and resettlement, 1.**

This sentence previously stated:

"There are several river valleys in Nepal, which are very productive and densely populated, such as Tumlingtar of Sanbhuwasabha district, Nepalthok of Kavrepalanchok district, and Manthali of Ramechhap district."

The corrected sentence appears below:

"There are several river valleys in Nepal, which are very productive and densely populated, such as Tumlingtar of Sankhuwasabha district, Nepalthok of Kavre district, and Manthali of Ramechhap district."

In the published article, there was an error. It was a grammatical error.

A correction has been made to **Results and Discussion, Migration and resettlement, 1**.

This sentence previously stated:

"Similarly, the lack of proper irrigation, and climate-induced disaster also compelled people to think of changing their settlement."

The corrected sentence appears below:

"Similarly, the lack of proper irrigation, and climate induced disasters also compelled people to think of changing their settlements."

The authors apologize for these errors and state that these do not change the scientific conclusions of the article in any way. The original article has been updated.

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Grain yield improvement in high-quality rice varieties released in southern China from 2007 to 2017

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In recent years, high-quality rice varieties have been widely cultivated for food production in southern China. However, changes in the yield performance of different high-quality rice varieties are still unclear. In this study, the yield and yield components of 710 different types (hybrid or inbred rice and *japonica* or *indica*) of high-quality rice varieties were investigated in six provinces from 2007 to 2017. The results showed that, from 2007 to 2017, the grain yield and yield traits, including the number of spikelets per panicle and seed-set percentage, of high-quality *indica* rice varieties increased significantly, while the number of panicles decreased only in *indica* inbred rice. The grain yield of high-quality *japonica* rice also increased significantly, whereas *japonica* hybrid rice increased the number of spikelets per panicle and decreased the number of panicles. Compared with inbred rice, hybrid rice had a significant increase in grain yield due to a higher number of spikelets, rather than a lower number of panicles and seed-set percentage. Meanwhile, *japonica* rice showed higher grain yield than *indica* rice, which was attributed to seed-set percentage and an optimized structure between the number of panicles and the number of spikelets. In addition, the coefficient of variation of the grain yield of *japonica* rice decreased, whereas that of *indica* rice increased over time, and those of the number of panicles and seed-set percentage remained stable. Among the six provinces, Zhejiang had the highest grain yield because the number of spikelets per panicle and seed-set percentage increased over time. Our results suggested that, based on an increase in the yield potential of high-quality rice varieties over the past 11 years, future breeding of high-quality rice should be emphasized to improve the number of panicles and seed-set percentage for hybrid rice and the number of spikelets for inbred rice, especially the grain weight for *indica* inbred rice.

KEYWORDS

southern China, high-quality rice varieties, grain yield, yield traits, breeding target

Introduction

Rice (*Oryza sativa* L.) is a staple cereal crop. China is the world's largest producer of rice, and its annual rice production accounts for almost 30% of total world production (FAO, 2018; Zhang et al., 2019). Sufficient food production can satisfy the need to feed the Chinese population (Tester and Langridge, 2010). Improving rice yield potential has been a major breeding goal in many countries for decades (Peng S. B. et al., 2008). As rice breeding, especially rice crossbreeding, has made rapid progress, the grain yield potential of rice has enhanced significantly in the last three decades (Yuan, 2017). Since 1980, rice production has increased by 59% despite a decline in available arable land. This is mainly due to the development of crossbreeding (Peng et al., 2009). Meanwhile, consumer demand for better quality and taste is also increasing due to better living standards and, therefore, the planting of high grain quality rice varieties is becoming more and more popular in rice production (Zeng et al., 2019). The proportion of high-quality rice in the rice market has increased significantly, and the Ministry of Agriculture and Rural Affairs is actively implementing green and efficient campaigns to promote high-quality and high-yielding varieties (Xu et al., 2021). High-quality rice varieties can enhance the market status and increase rice production benefits (Yang et al., 2015).

It is encouraging that, in the last 10 years, China has made great progress in developing high-quality rice production. The quality parameters of *japonica* and *indica* rice are different. Compared to *japonica,* better quality was achieved in *indica* rice (Zeng et al., 2019). The quality rate of inbred rice is higher than that of hybrid rice, and hybrid rice, especially three-line *indica* hybrid rice and *japonica* hybrid rice, has much room for improvement (Mao et al., 2017; Zeng et al., 2019). At present, the majority of rice varieties planted in China are mainly high-quality rice varieties, with the northern region having more high-quality rice varieties than the southern region (Wang et al., 2018).

Rice, which contains *indica* (*O. sativa* L. subsp. *indica*) and *japonica* (*O. sativa* L. subsp. *japonica*) in both hybrid and inbred rice varieties (Tripp et al., 2010), is widely planted in China. In China, *japonica* rice is cultivated mainly in northeastern China and in the lower reaches of the Yangtze River Basin and consists mainly of inbred varieties (Peng J. H. et al., 2008). *Indica* rice is grown mainly in southern China and consists mainly of hybrid varieties (Deng et al., 2006). The southern rice region is an important rice-producing region in China, including Zhejiang, Jiangxi, Hunan, Guangxi, Guangdong, and Fujian provinces along the Yangtze River. The boundaries of rice cultivation in China have moved northward due to the rising temperatures since the 1980s, and rice acreage is shrinking in southeast China (Yang et al., 2010; Liu et al., 2013).

The success of hybrid rice breeding greatly increases rice grain yield and has far-reaching significance in the developmental history of modern agriculture. Our previous studies (Zeng et al., 2019) elucidated the changing trend of rice quality of 710 high-quality rice varieties in the past 11 years, from 2007 to 2017, and analyzed rice quality change characteristics in different types of high-quality *indica* and *japonica* rice, as well as rice quality change characteristics in different provinces of the southern rice region. However, the yield characteristics of different types of high-quality rice released in southern China in the last few decades are not clear.

Continuous breeding of new high-yielding, good quality varieties is undoubtedly the most effective and economical means of increasing rice grain yield, and clarifying the formation rules of high-yielding rice varieties or types is an important goal of cultivation research. In addition, the grain yield of high-quality rice varieties is susceptible to environmental impacts and varies between specific years (Yoshida et al., 2006; Chen et al., 2008). We hypothesize that there are differences in rice grain yield traits from 2007 to 2017 among high-quality rice types from all the provinces in southern China. Therefore, the objectives of this study are to (1) compare the changes and status of major yield formation traits in 710 high-quality rice varieties; (2) explore differences in the yield characteristics of high-quality rice varieties in six provinces; and (3) ascertain strategies to improve high-quality rice in the future for southern China.

Materials and methods

Data collection and yield trait description

Between 2007 and 2017, we collated the major yield traits of 710 high-quality rice varieties selected from 1,797 rice varieties released in Jiangxi, Zhejiang, Fujian, Hunan, Guangxi, and Guangdong provinces. These traits were examined and approved by the provincial crop variety assessment committee (PCVAC) at the China Rice Data Center (2018). The high-quality rice varieties released did not include glutinous rice and sterile lines. Here, they were divided into four types, namely, 25 *japonica* inbred rice varieties, 25 *japonica* hybrid rice varieties, 138 *indica* inbred rice varieties, and 522 *indica* hybrid rice varieties, according to subspecies (*japonica* and *indica*) and breeding type (hybrid, inbred).

The yield traits of the collected data primarily include the number of panicles, the number of spikelets per panicle, seed-set percentage, grain weight, and grain yield. Data on the yield traits of the 710 rice varieties were measured by the Inspection and Testing Center of the Ministry of Agriculture's Rice and Product Quality Supervision Group according to the method of Peng et al. (2010). In this study, *japonica* rice varieties are primarily planted in Zhejiang province, and *indica* rice varieties are widely planted in the southern region of China, including the aforementioned six provinces, which have adequate temperature, light, and water resources. The annual average temperature is 15–24°C. The annual average rainfall is 950–2,500 mm. The number of sunshine hours ranges from 1,200 to 2,500 h, and the active accumulated temperature above 10°C (AAT) is 5,000–9,000°C (AAT= {mean daily temperature – 10} ×number of days). The soils are primarily red and paddy soils.

Statistical analysis

Means of yield traits and variation coefficients were performed with SPSS 22.0 statistical software (SPSS, Inc., Chicago, USA) to determine the least significant difference (LSD) at a p-value <0.05. The variation coefficient for each yield trait in every year of release was calculated as the ratio of the standard deviation (SD) to the average value of yield traits. A multivariate analysis of variance (ANOVA) was conducted to determine the effects of the subspecies (*indica* and *japonica*), the type of breeding (hybrid and inbred rice), and the year of release (as independent variables), as well as their levels of interaction in the yield traits of rice varieties (as dependent variables) at significance levels of 0.05, 0.01, and 0.001. The relative (%) genetic gain of the yield traits of high-quality rice varieties released annually was calculated by single linear regression, according to the methods of Feng et al. (2017).

$$Yi = a + b \cdot Xi,$$

where Yi is the value for each grain yield trait, Xi is the year of release for the cultivar i, a is the intercept of the equations, and b is the absolute slope. According to the release years for the six provinces, rice varieties could be divided into three stages, 2007–2010, 2011–2015, and 2016–2017.

Results

ANOVA for the yield traits of high grain quality rice types

Breeding type, subspecies, the year of release, and their interactions differed according to yield traits (Table 1). Breeding type was significant in relation to the number of panicles, the number of spikelets per panicle, seed-set percentage, and grain yield. Seed-set percentage and grain yield were also significantly affected by subspecies and the year of release. The number of spikelets per panicle was also significantly affected by subspecies. A significant interaction between the year of release and breeding type was observed for the number of panicles and seed-set percentage. For grain yield, a significant interaction between the year of release and subspecies was observed. A significant interaction between breeding type and subspecies was observed for the number of spikelets per panicle. A significant interaction between the year of release, breeding type, and subspecies was observed only for the number of panicles.

Differences in the yield performance between *japonica* and *indica* rice types

Compared with *indica* rice and *japonica* inbred rice, the number of panicles of *japonica* hybrid rice was lower by 18.7–28.6 and 34.9%, respectively (Table 2). However, the number of spikelets per panicle of *japonica* hybrid rice was higher by 33.2–39.6 and 43.3%, and significantly opposite trends were observed between inbred and hybrid varieties for both the number of panicles and the number of spikelets per panicle ($p < 0.05$). *Japonica* rice had a significantly higher seed-set percentage than *indica* rice, from 4.9 to 8.9%, and the same trends were observed between inbred and hybrid varieties. The grain weight of *indica* inbred rice was significantly lower than that of *japonica* rice and *indica* hybrid rice varieties by 14.7–17.1 and 17.7%, respectively, but no differences were found between the different types of *japonica* rice. *Japonica* rice had significantly higher grain yield than *indica* rice by 10.6–40.7%, and a significant inverse trend was shown between inbred and hybrid rice varieties.

Differences in the genetic gain of yield performance from 2007 to 2017

Genetic gains in the grain yield of both *japonica* and *indica* rice showed significantly increasing trends between 2007 and 2017 for both inbred and hybrid rice varieties (Table 3), suggesting that these high grain quality rice varieties had a high yield potential. Rice varieties between *indica* and *japonica* varied significantly in grain yield traits in the last 11 years. For *japonica* inbred rice, no significant changes in grain yield traits were observed. In contrast, *japonica* hybrid rice showed a significant decline in the number of panicles but a significant increase in the number of spikelets per panicle. Similarly, *indica* inbred rice showed a significant decline in the number of panicles but finally also increased yield with a significant increase in the number of spikelets per panicle and seed-set percentage. A significant increase in the number of spikelets per panicle and seed-set percentage in *indica* hybrid rice contributed to yield improvement.

Variation coefficient for different yield performance in high grain quality rice varieties

In three stages of high grain quality rice released during the study periods (2007–2010, 2011–2015, and 2016–2017), the subspecies also showed reduced variation coefficients in the number of panicles and seed-set percentage. *Japonica* inbred rice and *indica* varieties showed decreased variation coefficients in the number of spikelets per panicle but increased in grain weight. In contrast, *japonica* hybrid rice had increased variation

TABLE 1 Analysis of variance (ANOVA) of yield traits in rice.

Factors	Panicle number	Spikelet number per panicle	Seed-set percentage	Grain weight	Grain yield
Breeding type (hybrid, inbred)	16.40***	18.64***	15.74***	0.56^{ns}	20.93***
Subspecies (*japonica*, *indica*)	0.16^{ns}	4.01*	48.81***	0.74^{ns}	143.36***
Year released	1.08^{ns}	1.21^{ns}	2.80**	0.11^{ns}	8.93***
Year released × Breeding type	2.77**	0.64^{ns}	1.85*	0.15^{ns}	0.61^{ns}
Year released × Subspecies	1.11^{ns}	0.90^{ns}	1.50^{ns}	0.17^{ns}	2.18*
Breeding type × Subspecies	2.07^{ns}	8.96**	2.22^{ns}	1.68^{ns}	3.08^{ns}
Year released × Breeding type × Subspecies	3.19*	1.41^{ns}	0.54^{ns}	0.03^{ns}	0.65^{ns}

*, **, and ***Indicate significant differences at the probability levels of 0.05, 0.01, and 0.001, respectively; ns, indicate non-significant.

TABLE 2 Differences in the mean yield traits between *japonica* and *indica* types of high-quality rice.

Rice type	n	Panicle number (m^{-2})	Spikelet number per panicle	Seed-set percentage (%)	Grain weight (mg)	Grain yield (t hm^{-2})
Japonica inbred	25	305.2a	130.9c	88.6a	25.8a	8.43b
Japonica hybrid	25	226.2c	230.8a	84.9b	25.1a	9.34a
mean		265.7	180.9	86.7	25.5	8.89
Indica inbred	138	291.0a	139.5c	82.9c	21.4b	6.64d
Indica hybrid	522	268.6b	154.2b	80.7d	26.0a	7.62c
mean		279.8	146.9	81.8	23.7	7.13

Different lowercase letters between different rice types in the same column are significant at a p-value < 0.05.

TABLE 3 Genetic gain (%) of yield traits in high grain quality rice varieties.

Rice type	*n*	Panicle number (m^{-2})	Spikelet number per panicle	Seed-set percentage (%)	Grain weight (mg)	Grain yield (t hm^{-2})
Japonica inbred	25	Ns	ns	Ns	ns	12.40***
Japonica hybrid	25	−0.74***	13.02***	Ns	ns	11.43***
Indica inbred	138	−0.24***	1.37***	0.30**	ns	5.06***
Indica hybrid	522	Ns	1.52*	0.41***	ns	6.13***

*, **, and ***Indicate significant differences at the probability levels of 0.05, 0.01, and 0.001, respectively; ns, indicate non-significant.

coefficients in the number of spikelets per panicle but decreased grain weight. In addition, variation coefficients of grain yield decreased in *japonica* rice but increased in *indica* rice (Table 4).

For *indica* inbred rice, variation coefficients of the number of panicles and grain yield were the lowest in Guangxi province among the six provinces. Relatively low variation coefficients of the number of spikelets per panicle and grain weight were observed in Hunan province, and those of the seed set were found in Zhejiang province. In contrast, variation coefficients of each yield component trait in Fujian province were relatively high. For *indica* hybrid rice, variation coefficients of the number of panicles, the number of spikelets per panicle, and grain yield were lower in Guangdong province than in the other provinces, while those of the seed-set percentage and grain weight decreased in Hunan province. In contrast, variation coefficients of each yield component trait in Jiangxi province were high (Table 5).

Yield performance of high grain quality rice for each variety type in six provinces

From 2007 to 2017, the grain yield of high-quality rice varieties showed an increasing trend in all six provinces except Fujian, with the largest increases of 22.5%, 22.0%, and 25.3% in Zhejiang, Hunan, and Jiangxi provinces, respectively (Figure 1A). Of the three stages (2007–2010, 2011–2015, and 2016–2017), Fujian province had relatively high grain yield

TABLE 4 Variation coefficients for the yield traits of the released inbred and hybrid rice varieties.

Rice type	Year	Panicle number (m^{-2})	Spikelets number per panicle	Seed-set percentage (%)	Grain weight (mg)	Grain yield ($t\ hm^{-2}$)
Japonica inbred	2007–2010	10.21	14.25	4.94	5.33	6.56
	2011–2015	19.05	9.69	5.55	3.26	9.83
	2016–2017	6.61	4.25	2.62	6.69	3.48
	Mean	11.96ab	9.40b	4.37ab	5.09*c*	6.62b
Japonica hybrid	2007–2010	9.11	9.47	5.76	6.97	3.62
	2011–2015	21.31	10.82	8.10	11.65	8.78
	2016–2017	12.72	15.48	4.65	6.68	5.98
	Mean	14.38ab	11.92b	6.17a	8.43b	6.13b
Indica inbred	2007–2010	12.24	11.87	4.10	12.43	6.83
	2011–2015	6.73	9.97	4.75	11.42	5.75
	2016–2017	8.82	8.47	3.59	14.46	8.97
	Mean	9.26b	10.10b	4.15b	12.77a	7.18b
Indica hybrid	2007–2010	15.36	59.44	6.19	9.07	8.66
	2011–2015	14.79	17.04	4.70	10.07	9.58
	2016–2017	14.78	14.85	4.05	79.80	10.56
	Mean	14.98a	30.44a	4.98ab	32.98a	9.60a

Different lowercase letters between different rice types in the same column are significant at a p-value < 0.05.

TABLE 5 Changes in variation coefficients for the yield traits of high grain quality rice varieties in different provinces.

Rice type	Province	Panicle number (m^{-2})	Spikelet number per panicle	Seed-set percentage (%)	Grain weight (mg)	Grain yield ($t\ hm^{-2}$)
Japonica inbred	Zhejiang	12.72	11.27	4.54	5.23	10.31
Japonica hybrid	Zhejiang	18.90	21.07	5.11	7.28	7.50
Indica inbred	Zhejiang	8.71	15.48	1.99	6.77	3.94
	Jiangxi	10.49	17.90	5.74	10.46	15.48
	Hunan	18.06	3.56	5.14	4.01	11.21
	Guangxi	5.01	11.68	7.34	9.81	1.93
	Guangdong	9.23	8.10	3.84	12.03	6.53
	Fujian	29.23	53.07	6.54	8.86	19.27
Indica hybrid	Zhejiang	11.66	18.52	5.14	7.97	9.03
	Jiangxi	12.19	60.68	5.81	67.83	10.14
	Hunan	9.16	9.17	3.30	5.17	11.15
	Guangxi	8.74	10.89	4.53	9.96	5.89
	Guangdong	8.01	7.57	4.21	8.99	5.13
	Fujian	11.36	17.24	4.66	6.30	10.65

in both the first and second stages, followed by Zhejiang province in the third stage. In the other provinces except Jiangxi, the number of panicles of high-quality rice varieties showed decreasing trends, with a relatively larger number in Hunan in the first stage and in Jiangxi in the next two stages (Figure 1B). The number of spikelets per panicle of those decreased in Guangxi but increased in other provinces, especially Zhejiang in the third stage, and was relatively high in Guangxi province in the first stage (Figure 1C). The seed-set percentage in all provinces except Guangxi showed an increasing trend, and the growth rate was relatively stable (Figure 1D). Zhejiang province had a higher seed-set percentage in all three stages. Grain weight in all provinces except Zhejiang showed an increasing trend, with Fujian province showing a high value in the previous two stages and Jiangxi province showing a rapid increase in the third stage (Figure 1E).

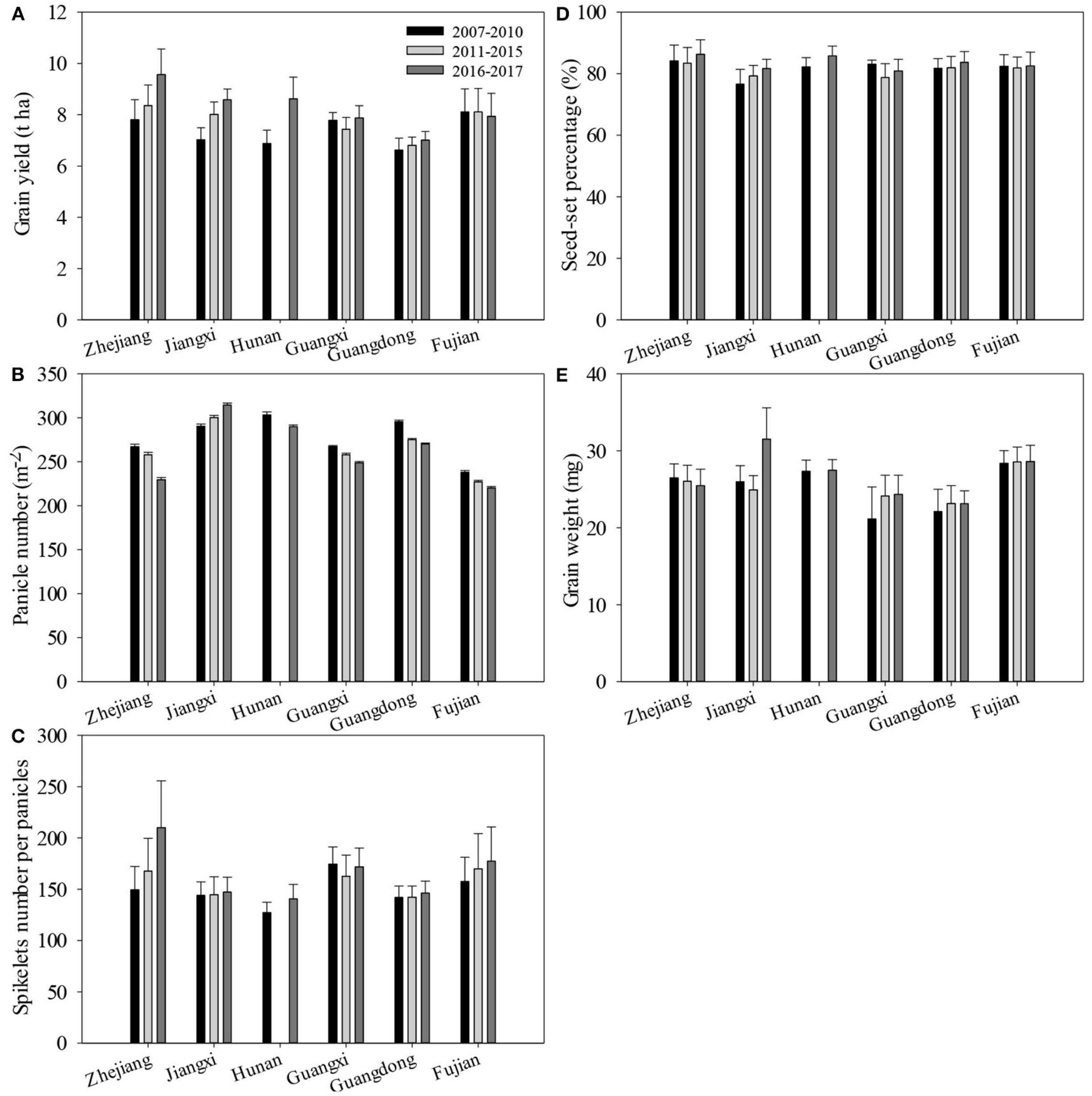

FIGURE 1
Grain yield **(A)**, the number of panicles **(B)**, the number of spikelets per panicles **(C)**, seed-set percentage **(D)**, and grain weight **(E)** of high grain quality rice varieties in six provinces.

Relationships between grain quality and yield in high-quality rice varieties

The number of panicles and seed-set percentage and grain weight were positively and negatively correlated with the head rice rate, respectively (Figure 2). The chalkiness rate and chalkiness degree were negatively and positively associated with the number of panicles and seed-set percentage, while grain weight and grain yield were positively associated with the chalkiness rate (Figure 2). There were negative relationships between amylose content, the number of spikelets, seed-set percentage, and grain yield (Figure 2). The number of panicles and the number of spikelets per panicle were negatively and positively correlated with gel consistency, respectively (Figure 2).

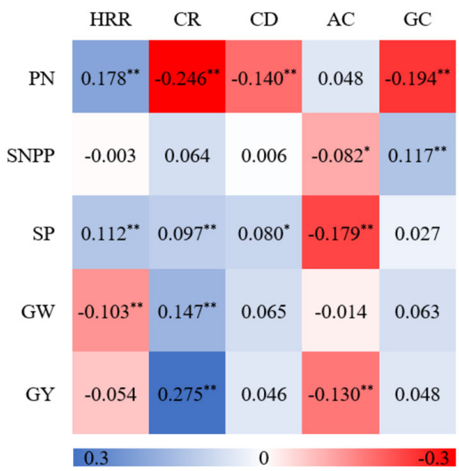

FIGURE 2
Correlation coefficient between grain yield and quality of high-quality rice from 2007 to 2017 ($n = 710$). *Correlation is significant at the 0.05 level, while ** correlation is significant at the 0.01 level (two-tailed). PN, panicle number; SNPP, spikelet number per panicles; SP, seed-set percentage; GW, grain weight; GY, grain yield; HRR, head rice rate; CR, chalkiness rate; CD, chalkiness degree; AC, amylose content; GC, gel consistency.

Discussion

Changes in grain yield and yield traits for selected high-quality rice varieties

In the present study, the grain yield of high-quality rice varieties *indica* or *japonica* rice and hybrid or inbred rice continued to increase between 2007 and 2017 (Table 3). These were mainly due to the increase in grain yield per unit rather than the rice planting area, so the yield per unit was the deciding factor for the increase in China's total grain yield (Chen et al., 2012). Zhejiang, Jiangxi, and Hunan provinces are mainly located in the rice preponderance area of the Yangtze River Basin, while Guangdong, Guangxi, and Fujian provinces are mainly located in the rice preponderance area of the southeast coast of China (Peng, 2014). In this study, for these three stages, grain yield increased in most provinces except Fujian, and Guangxi and Guangdong provinces had a small increase in grain yield trends from 2007 to 2017 (Figure 2). The concentration degree of rice production and background soil fertility of rice fields are higher in the rice preponderance area of the Yangtze River Basin than in the rice preponderance area of the southeast coast of China (Li J. J. et al., 2016). Second, the plantation area of single crop rice in the rice preponderance area in the Yangtze River Basin has increased year by year, which is the main reason for the large increase in yield per unit area in Hunan and Jiangxi provinces (Chen et al., 2012).

Increasing the yield potential of super rice employed involves a combination of ideotype breeding, heterosis utilization, and the goal of modifying plant architecture, and heterosis is a time tested strategy to achieve increased yield potential (Khush, 2005). These approaches result in the adoption of semi-dwarf cultivars for better lodging resistance and the exploitation of heterosis, which is known to substantially increase rice yields over the last half century (Lei et al., 2010; Wing et al., 2018). The number of panicles and the number of spikelets per panicle are important components of ideotype in super rice (Deng et al., 2004). In this study, the number of panicles in the *japonica* hybrid and *indica* inbred rice decreased significantly over time, but no change was observed in the *japonica* inbred and *indica* hybrid rice (Table 3), while the number of panicles in the hybrid rice largely varied over time (Table 4). Thus, improving the number of panicles for high-quality hybrid rice might be another breeding target. Previous studies showed that the breeding approach of a high number of panicles in rice production was feasible because the *MOC1* gene (the first cloned gene related to rice tillering) on chromosome 6 was mapped, and the functional analysis proved that this gene was a key regulatory gene in regulating rice tillering (Li X. Y. et al., 2003). Subsequently, the following genes related to rice tillering, such as *OsTB1, D14, MT1,* and *HTD2,* were discovered by other researchers, supporting our results (Li et al., 2003; Arite et al., 2009; Liu et al., 2009; Zhou et al., 2009). In addition, in this study, high-quality *indica* hybrid rice showed large variation coefficients in the number of spikelets per panicle over time (Table 4), suggesting that it should also be improved. As genes that regulate tillers and spikelets tend to be highly pleiotropic and affect many different traits, this study on obtaining high yield potential might involve balancing the different traits (Xing and Zhang, 2010). When considering the improvement of rice yield, it is important to characterize the entire regulatory network rather than component traits or individual genes. As a result, this can verify the breeding achievements related to the high yield of high-quality rice varieties. In fact, a proposal for ideotype breeding is to improve the efficiency of canopy radiation use (Guo et al., 2020). Hence, a perfect physiological function (such as photosynthesis capacity, biomass accumulation, and translation ability) of tillering could achieve ideotype breeding of high-quality varieties because of their high yield potential (Xiao F. et al., 2021).

The seed-set percentage of rice was mainly determined by flowering fertilization and grain filling (Deng et al., 2021). Previous studies demonstrated that spikelet fertility is one of the most environmentally sensitive components of rice grain production (Suzuki et al., 2015). Our research indicated that the seed-set percentage in *indica* rice increased significantly over time, but no change was observed in *japonica* rice. In the context of global warming, the process of improving high-quality *japonica* rice is continuously developing because *japonica* rice is relatively weak in heat resistance (Wang et al., 2019). Meanwhile, the subspecies showed a small difference in seed-set percentage, and high-quality *indica* rice showed large variation coefficients in grain weight in three stages (Table 4), implying that they should be improved in future breeding. However, there were no significant changes in grain weight, indicating that grain weight is not the main factor affecting grain yield over time. An increase in the grain yield of *japonic*a hybrid rice was mainly due to the number of spikelets per panicle rather than the number of panicles; an increase in the grain yield of *indica* rice was mainly related to the number of spikelets per panicle and seed-set percentage in the last 11 years.

Differences in grain yield traits between high-quality rice types in southern China

Zhang et al. (2013) reported that the grain yield of *japonica* rice was significantly higher than that of *indica* rice when comparing local representative *indica* and *japonica* rice varieties in the lower reaches of the Yangtze River in China. In Liaonig province, the yield of northeast *japonica* rice increased by 13.48% compared with control *indica* rice (Gao et al., 2013). We also saw similar yield results in the subspecies. The reason might be that the storage substance of *japonica* rice before the heading stage was higher than that of *indica* rice, and the amount of nutrients transported to grains was larger (Xu et al., 2018). *Indica* rice showed a quicker senescence degree of leaves and roots than *japonica* rice at the grain filling stage (Gong et al., 2014). In addition, in the late growth stage, *japonica* rice could adapt to low temperatures and was still well filled in the glumes, even though the number of spikelets in *japonica* rice was equal to or slightly less than that in *indica* rice (Zhang et al., 2013). Meanwhile, the results showed that the yield of hybrid rice was significantly higher than that of inbred rice in the same subspecies, indicating that the breeding work of hybrid rice had made great progress in the past 11 years (Table 2).

In this study, the number of panicles of hybrid rice was significantly decreased compared with inbred rice (Tables 2, 3). In contrast, hybrid rice significantly increased the number of spikelets per panicle in the same subspecies (Tables 2, 3). Hybrid rice with a large heavy panicle type showed relatively high yield (Sheehy et al., 2001), and our results were similar to those of Lin (2008). The reason might be that a decrease in the number of panicles and an increase in the number of spikelets per panicle could significantly improve the grain–panicle structure, rationally use light conditions, and enlarge the sink capacity to promote the coordinated development of grain yield and quality (Chen et al., 2018). However, the opposite trends of the number of panicles and the number of spikelets per panicle in breeding type and subspecies rice varieties could not be solved with ideal plant type alone because it involves population effects, which can also be verified by the results mentioned above. Although single trait enhancement increased yield in our study, it was always difficult to coordinate the factors of population structure. Therefore, the optimization of the contradiction between the number of panicles and the number of spikelets will be of great significance through agricultural measures such as water and fertilizer management or genetic improvement for the use of yield potential and the coordination of high-quality rice varieties, especially varieties of different subspecies and types of breeding. In addition, high variation coefficients were found for yield traits in both the number of panicles and the number of spikelets per panicle in six provinces, especially Fujian, possibly suggesting a worse climatic environment to influence rice growth (Table 5).

Grain weight per panicle (GWPP) is determined by the number of spikelets per panicle and grain weight (Chen et al., 2007), and increased GWPP can achieve super high yield (Yang et al., 2006). On the other hand, an increase in the number of spikelets per panicle is accompanied by a decrease in seed-set percentage (Wu et al., 2010). Similar results were obtained in the present study (Table 2). Xu et al. (2006) reported that secondary panicle branches usually had a lower seed-set percentage. On the contrary, in breeding varieties with vascular bundles developed at the panicle neck, a large number of primary branches and secondary branches on the upper panicle could effectively solve the contradiction between the number of spikelets per panicle and seed-set percentage (Xu et al., 1998; Xu et al., 2006). In the present study, *japonica* rice had a significantly higher seed-set percentage than *indica* rice for high-quality rice breeding types in the last 11 years. The grain filling time of *japonica* rice was longer and more stable, especially in the late filling stage and even when the filling of inferior grain was also better (Gong et al., 2014). Therefore, the optimized yield components of high-quality *indica* rice should possess a high number of spikelets and seed-set percentage, whereas the relatively lower tillers of inbred *indica* rice should be optimized for this study. Due to complex and negative relationships between yield and quality traits, the breeding of high-yielding, high-quality varieties is difficult (Xiao N. et al., 2021). However, the breeding of high-yielding, high-quality rice varieties may be promising, due to recent technological advances in genome biology such as genome editing and molecular breeding (Wing et al., 2018).

Synergistic improvement strategy of high-quality rice yield and quality

The super high yield of rice remains the eternal direction of research objectives in China. However, with the improvement of people's living standards, the demand for rice has diversified (Zhang et al., 2021). High yield and high quality are urgent problems that must be solved in high-quality rice. Correlation analysis showed that grain yield was positively correlated with the chalkiness rate and negatively correlated with amylose, which were beneficial to the synergistic improvement of rice eating quality and grain yield, but was not conducive to the improvement of rice appearance quality (Figure 2). During carbon and nitrogen metabolism at the filling stage of rice grain, protein synthesis increases, resulting in improved rice yield (Xiong et al., 2021). Reduced amylose content resulted in an uneven arrangement of rice starch granules, loose tissues in the endosperm, and finally increased the chalkiness rate (Yang et al., 2019). Unlike the number of spikelets per panicle, seed-set percentage, and grain weight, an inverse correlation was observed between the panicle number with appearance (chalkiness rate and chalkiness degree) and eating quality (amylose content and gel consistency) (Figure 2). Attention should be paid to the breeding goal of ensuring rice with high yield and high quality. In addition, grain weight is also different from the number of spikelets per panicle and seed-set percentage. The former has a negative correlation with the head rice rate, while the latter has a positive correlation with the head rice rate (Figure 2). The results showed that an adequate reduction of grain weight and the increase in the number of panicles and seed-set percentage were beneficial to improve the processing quality.

Conclusions

Grain yield increased significantly in each subspecies (*japonica* and *indica*) and breeding type (hybrid, inbred) of high-quality rice varieties from 2007 to 2017. The number of spikelets per panicle, instead of the number of panicles, contributed to the grain yield of *japonic*a hybrid rice, but both the number of spikelets per panicle and seed-set percentage could contribute to the grain yield of *indica* rice over time. *Japonica* rice showed significantly higher grain yield than *indica* rice due to the higher seed-set percentage and better optimized yield trait structure such as the number of panicles and the number of spikelets per panicle and the hybrid rice achieved high grain yield compared with the inbred rice, which was mainly attributed to the higher number of spikelets per panicle. Additionally, variation coefficients of grain yield showed a decreasing trend in *japonica* rice in the past 11 years but had an increasing trend in *indica* rice, and variation coefficients for both the number of panicles and seed-set percentage were also reduced in the subspecies, suggesting that *japonica* rice varieties had stable grain yields. For the past 11 years, the grain yield of high-quality rice varieties had a higher increase in Zhejiang, Hunan, and Jiangxi provinces than in other provinces, especially in Zhejiang province, which was supported by reasonable yield components, such as the highest number of spikelets per panicle and seed-set percentage. Future high-quality rice breeding should focus on the optimized yield components, with hybrid rice focusing on improving the number of panicles and seed-set percentage and inbred rice improving the number of spikelets, especially the grain weight for *indica* inbred rice.

Data availability statement

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

Author contributions

HW, RX, and YZh: investigation, data curation, and writing—original draft. XT: software, methodology, and visualization. XP, YoZ, SH, QS, and XX: writing—review and editing. JZ: validation and project administration. YaZ: writing—review and editing and conceptualization. All authors contributed to the article and approved the submitted version.

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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.

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Coupling optical and SAR imagery for automatic garlic mapping

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Accurate garlic identification and mapping are vital for precise crop management and the optimization of yield models. However, previous understandings of garlic identification were limited. Here, we propose an automatic garlic mapping framework using optical and synthetic aperture radar (SAR) images on the Google Earth Engine. Specifically, we firstly mapped winter crops based on the phenology of winter crops derived from Sentinel-2 data. Then, the garlic was identified separately using Sentinel-1 and Sentinel-2 data based on the winter crops map. Additionally, multi-source validation data were used to evaluate our results. In garlic mapping, coupled optical and SAR images (OA 95.34% and kappa 0.91) outperformed the use of only optical images (OA 74.78% and kappa 0.50). The algorithm explored the potential of multi-source remote sensing data to identify target crops in mixed and fragmented planting regions. The garlic planting information from the resultant map is essential for optimizing the garlic planting structure, regulating garlic price fluctuations, and promoting a healthy and sustainable development of the garlic industry.

KEYWORDS

garlic identification, phenology, multi-source image coupling, Google Earth Engine, Sentinel-1/2

Introduction

Garlic is one of the primary economic crops (e.g., garlic, peanut, rape, sugar beet, sugarcane, and cotton) in China. According to statistics from the United Nations Food and Agriculture Organization (FAOSTAT, 2020), garlic production in China reached 23.30 million tons in 2019, which made China the largest garlic planting and production region in the world. Due to the small area and scattered distribution of garlic crops, few studies have been able to map them accurately, which hinders their precise management (Zhang et al., 2019; Guo et al., 2022b).

Traditionally, information about the garlic planting area is mainly obtained based on a sampling or field survey. Such methods are not only vulnerable to subjective factors (Liu et al., 2018a) but they also have a long cycle, are labor-intensive, and are time-consuming (Siyal et al., 2015; Verma et al., 2017). Satellite imagery has become a viable crop mapping data source, due to its high mapping efficiency and low cost (Massey et al., 2017; Vallentin et al., 2021; Guo et al., 2022a), and it is widely used in many fine-mapping fields, such as urban land mapping (Liu et al., 2018b), water surface area change (Xia et al., 2019; Zhao et al., 2022), forest degradation (Bullock et al., 2020), cropland classification (Poortinga et al., 2019), and wetland classification (Amani et al., 2019).

At present, the accuracy of the garlic extraction based on remote sensing data is mostly unsatisfactory. Qu et al. (2021) attempted to map garlic distribution using the threshold method and Landsat images. However, the limited temporal resolution of the Landsat satellite makes it difficult to obtain sufficient high-quality images during the growing season, which can easily ignore spectral differences of crops. Therefore, the accuracy and timeliness of the results are difficult to guarantee. Lee et al. (2015) attempted to use ultra-high-resolution Worldview-2 satellite images to map garlic distribution. However, the high cost and limited coverage of a single image restrict their application to a large region. Similarly, although Unmanned Aerial Vehicle (UAV) imagery provides more spatial details, it usually requires many images to fully cover the study area and is difficult to apply to large areas. The Sentinel-2 (S2) imagery provided a temporal resolution of 5 days and a spatial resolution of 10 m, providing an opportunity for the identification of broken and scattered garlic distributions.

The quality of Sentinel-1 (S1) imagery is independent of weather conditions (Du et al., 2015; Oyoshi et al., 2016), which compensates for the lack of optical observations due to bad weather during the crop growth cycle (Torbick et al., 2017). In addition, S1 SAR images are very sensitive to plant structure (Chauhan et al., 2020; Schlund and Erasmi, 2020), which is conducive to monitoring crops with different growth structures in the same growth cycle. Agmalaro et al. (2021) attempted to map garlic distribution based on Sentinel-1 images using the support vector machine (SVM) approach. Similarly, Sentinel-1 images and the decision tree method were also used to identify garlic distributions (Komaraasih et al., 2020). However, the results show that the classification accuracy using only S1 images is worrisome (76%−78%). This is due to the phenomenon of "different objects with the same spectrum" (Cai et al., 2020), which usually occurs in crops with a similar growth cycle, such as garlic and winter wheat.

Garlic extraction approaches thus far can be roughly divided into two types. The first approach is to use machine learning methods with the spatial statistics of spectral bands, vegetation indices (VIs), and texture in the single- or multi-date optical images as input variables (Guo et al., 2022b). Lee et al. (2015) extracted garlic locations using random forest (RF) and maximum likelihood (ML) classifiers with the spectral features of the garlic as input variables. VIs were also used as input variables to distinguish the garlic and other vegetation types through the ML classifier (Lee et al., 2016). Di et al. (2018) constructed the garlic classification indexes using the digital number (DN) characteristics of different ground object images and extracted those of garlic by SVM. This approach requires a large number of local training samples and is therefore limited to large-scale accurate models. Additionally, complex feature combinations and indices may lead to overfitting (Graesser and Ramankutty, 2017). The second approach is to calculate the temporal statistics of spectral bands, VIs, and backscatter coefficients of synthetic aperture radar (SAR) data in the time series data of individual pixels and use decision trees or rule-based algorithms to identify the garlic (Qu et al., 2021). Different crops have different phenological characteristics in a specific period (Bargiel, 2017; Massey et al., 2017), which are recorded in the time series data and can be used for the classification of individual pixels. Moreover, the irregular interval of time series is critical to support the complete development of classification models (Qiu et al., 2017). Training samples of the garlic, winter wheat, and other crops were overlaid with these phenological characteristic layers to carry out a signature analysis. Based on the results of signature analysis, classification rules can be built and the garlic can be identified by a decision classification approach. These phenology-based algorithms have been successfully applied for mapping winter wheat (Song and Wang, 2019), rice (Yang et al., 2021), corn (You and Dong, 2020), and soybean (You et al., 2021). As a winter crop, garlic has significant phenological characteristics different from other winter crops in specific growth stages. Therefore, it is necessary to fully exploit these differences to achieve a fine mapping of garlic.

We hypothesized that there are optimal combinations of sensors and indices to achieve the best garlic recognition. To test this hypothesis, we analyzed the combined effects of different sensors and indices and aimed to understand how S1 and S2 contribute to garlic identification, which combination of satellite sensors enables optimal mapping of the garlic, and which indexes can optimize the recognition accuracy of the garlic and improve the classification efficiency.

Cropping systems in China are characterized by smallholder farms, whose majority of cropland field size is $<$ 0.04 ha (Tan et al., 2013). Therefore, complex mixed planting patterns and small, fragmented blocks in Qi County present a challenge for the remote sensing recognition of garlic in this region. The crops in Qi County are mainly divided into winter crops and non-winter crops, and its winter crops mostly consist of garlic and winter wheat. Considering the above limitations of remote sensing in garlic mapping and the actual demands of farmers and the local government for timely and accurate information on garlic plantations, we proposed an automatic garlic mapping framework (Figure 1). This study had the following objectives: (1) monitoring the phenological characteristics of garlic in time; (2) developing an automatic mapping framework to map the garlic at a 10-m resolution based on multi-source remote sensing data and phenological characteristics; (3) exploring the potential of the coupling of the optical and SAR images to map the garlic in a mixed planting region; (4) providing a guideline for future approaches of modern crop management practices and giving an objective overview of suitable sensors and indices.

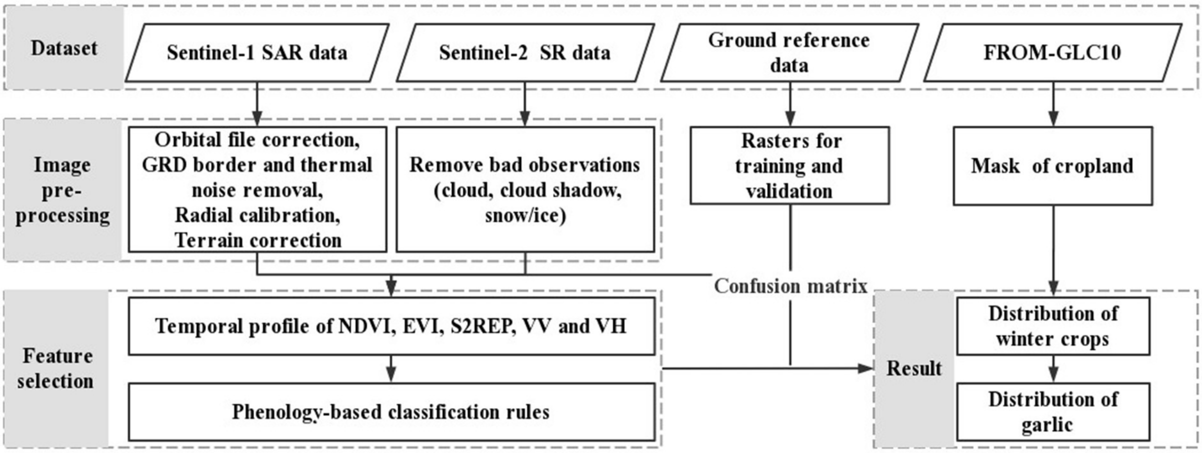

FIGURE 1
The framework for mapping the garlic.

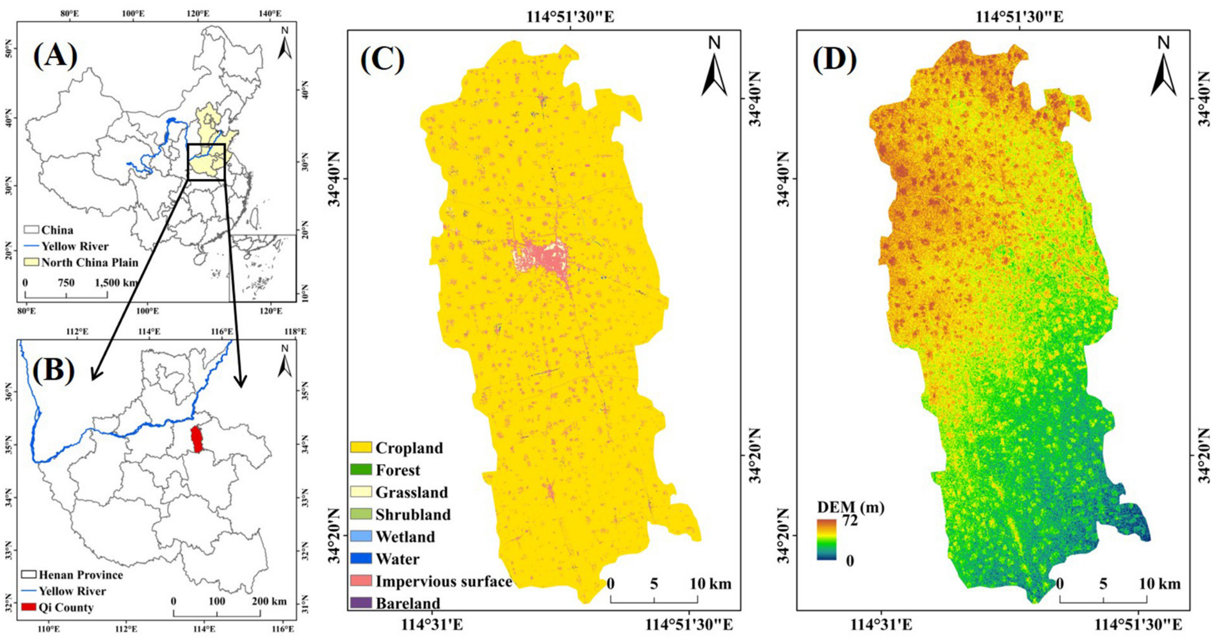

FIGURE 2
(A) The location of Qi County in China, **(B)** Enlarged map showing Qi County, Henan Province **(C)** Spatial pattern of the land cover types, and **(D)** Digital Elevation Model (DEM).

Materials and methods

Study area

Qi County lies in the east of Henan Province, the South Bank of the lower Yellow River, and the hinterland of North China Plain (Figures 2A,B). Qi County has a total area of 1,531 km^2, including 1,420 km^2 of cropland (Figure 2C), and a temperate continental monsoon climate. The total terrain is high in the northwest and low in the southeast (Figure 2D). Its main winter crops are garlic and winter wheat. According to statistics, garlic production reached 84.8 tons in 2019 (https://data.cnki.net/Yearbook/, last accessed [December 15, 2021]), ranking first at the county level in China. Garlic and winter wheat are usually sown around October and harvested around June in next year of Qi County.

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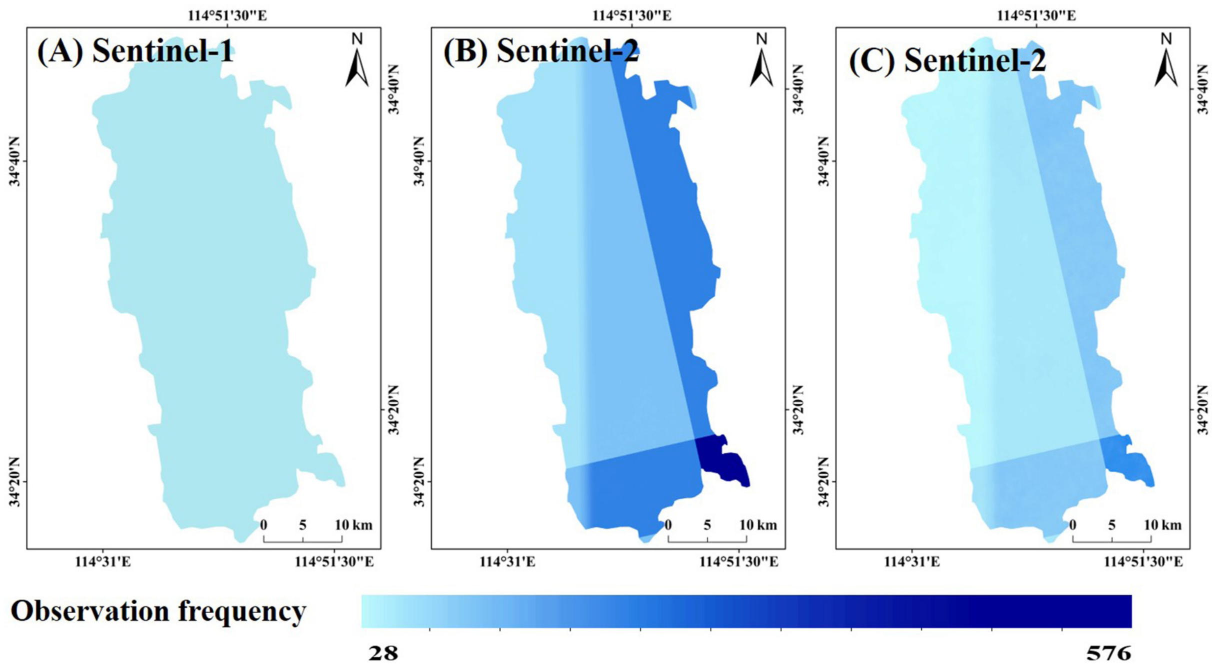

FIGURE 3
Numbers of observations for individual pixels during the study period. **(A,B)** The spatial distributions of total observations for individual pixels for S1 and S2. **(C)** The spatial distributions of good-quality observations for individual pixels for S2.

Datasets and preprocessing

Sentinel-1 images

The European Space Agency (ESA) S1 is a SAR system composed of S1A and S1B satellites, which were launched in April 2014 and April 2016, respectively. They are available at https://sentinel.esa.int/. We selected data from the interferometric wide swath (IW) mode, which is the default operational mode over land. The IW mode is in the dual polarization of vertically transmitted and horizontally received (VH) and vertically transmitted and vertically received (VV) polarizations with a temporal resolution of 12 days and a spatial resolution of 5 × 20 m (Torres et al., 2012). From October 1, 2019, to July 1, 2020, 30 S1 images as Level-1 ground range detected (GRD) were collected (Figure 3A), corresponding to "COPERNICUS/S1_GRD" of the Google Earth Engine (GEE) cloud platform.

Some preprocessing algorithms were applied to S1 images, including orbital file correction, GRD border and thermal noise removal, radiometric calibration, and terrain correction. First, the orbit file was used to provide accurate satellite positions for each scene. Second, GRD border and thermal noise removal were applied to each scene to remove the additional noise and reduce the discontinuity in the subsamples of each scene. Third, the digital pixel value was transformed into a SAR backscattering coefficient by radiometric calibration. Finally, terrain correction was performed for each scene to correct the geometric distortion caused by the side view geometry of the acquisition system, after which shortened mask correction was performed.

Sentinel-2 images

S2 Multi-Spectral Instrument (MSI) data includes S2A and S2B images provided by the European Space Agency (ESA), and the revisit cycle of the two satellites is 5 days (Drusch et al., 2012). Because top of atmosphere (TOA) data is sensitive to changes in atmospheric composition over time, surface reflection (SR) data was selected (Jin et al., 2019). Red, near-infrared (NIR), and blue bands with a spatial resolution of 10 m and red edge (RE) bands with a spatial resolution of 20 m were used. The RE bands were resampled to 10 m by bicubic resampling to match other bands. From October 1, 2019, to July 1, 2020, 576 S2 images were collected, corresponding to "COPERNICUS/S2_SR" on the GEE cloud platform.

The quality of S2 data was assessed by the quality assessment band (QA60) in the metadata, which identifies the clouds and cloud shadows in the image as bad-quality observations and stored them as NODATA in the image (Wang et al., 2020). Specifically, since dense clouds have a high reflectance in the blue spectral region (B2), the method used to identify dense cloud pixels is based on the B2 reflectance threshold (SWIR reflectance in B11 and B12 are also used to avoid snow/cloud confusion).

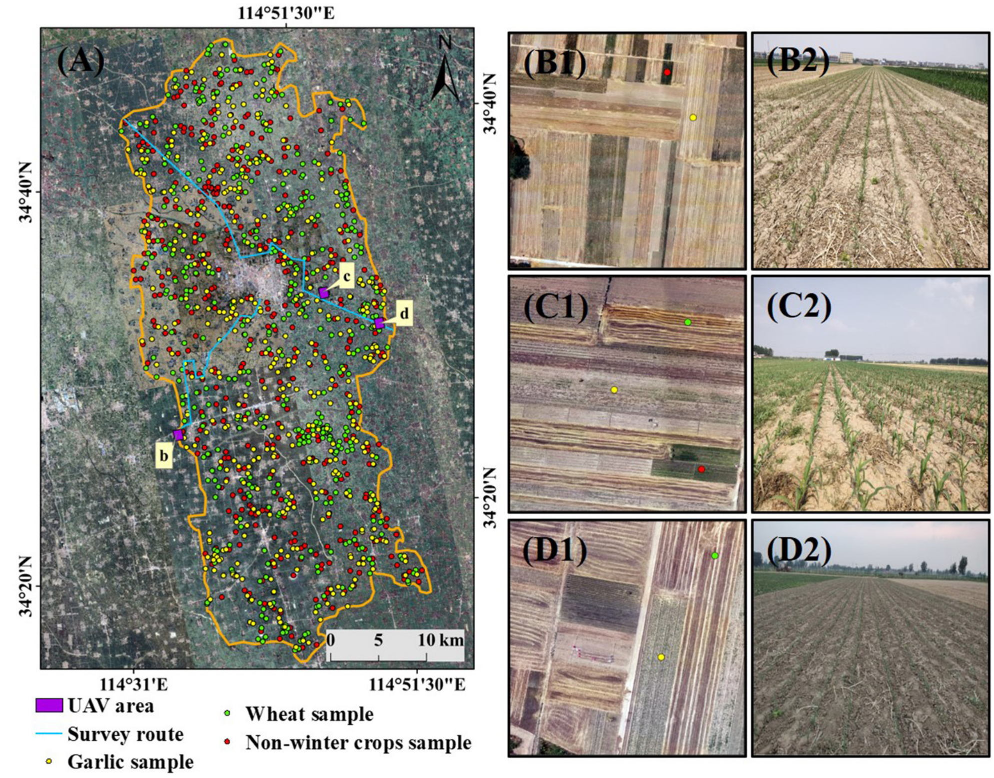

FIGURE 4
(A) Distribution of validation samples, including garlic, wheat, and non-winter crops. **(B1–D1)** Are the UAV images. **(B2–D2)** Are the ground observations from the field camera photograph. **(B1,B2)**, **(C1,C2)**, and **(D1,D2)** correspond to b, c, d in **(A)**, respectively.

B10 corresponds to a high atmospheric absorption band, which means only high-altitude clouds can be detected. Additionally, since cirrus clouds are semi-transparent, they cannot be detected in the B2 blue band. Therefore, a pixel with low reflectance in the B2 band and high reflectance in the B10 band has a good probability of being cirrus cloud (a filter using morphology-based operations is also applied on both dense and cirrus masks performing). After preprocessing the image in the above steps, the total observations and good-quality observations of individual pixels were calculated, respectively (Figures 3B,C).

Ground reference data

The ground reference data of different crop types are critical to verify the crop classification algorithm. Ground reference data was collected considering the following three aspects. First, based on the Google Earth image, the stratified random sampling method was used to collect ground training and validation samples. Google Earth images with 1-m spatial resolution clearly show different ground feature types, such as the garlic field, winter wheat field, bare land. Second, two investigation routes were designed, and fieldwork was conducted to collect geo-referenced field photos from March to June 2020. These field photos include different crop types such as garlic, winter wheat, and peanuts. Third, during the fieldwork, multiple multispectral images were obtained through UAV. The spatial resolution of these multispectral images is as high as 0.1 m, which facilitates the identification of garlic among other crop types. Through the images obtained considering the above three aspects, 412 garlic samples, 451 non-garlic winter crop samples, and 453 non-winter crop samples were collected, and their spatial distribution is shown in Figure 4.

Land cover data

Cropland data from the FROM-GLC10 land cover product were used to mask all S2 datasets to delimit the cropland extent (Chen et al., 2019). This product was generated by RF based on S2 images and reported the cropland in 2017 with a 10-m spatial resolution. The map can be freely accessed at http://data.ess.tsinghua.edu.cn (last accessed December 15, 2021).

Methods

Figure 5 shows the algorithm framework for producing the 2020 garlic distribution map. Generally, the garlic is extracted in two steps: (1) extraction of winter crops, which is the

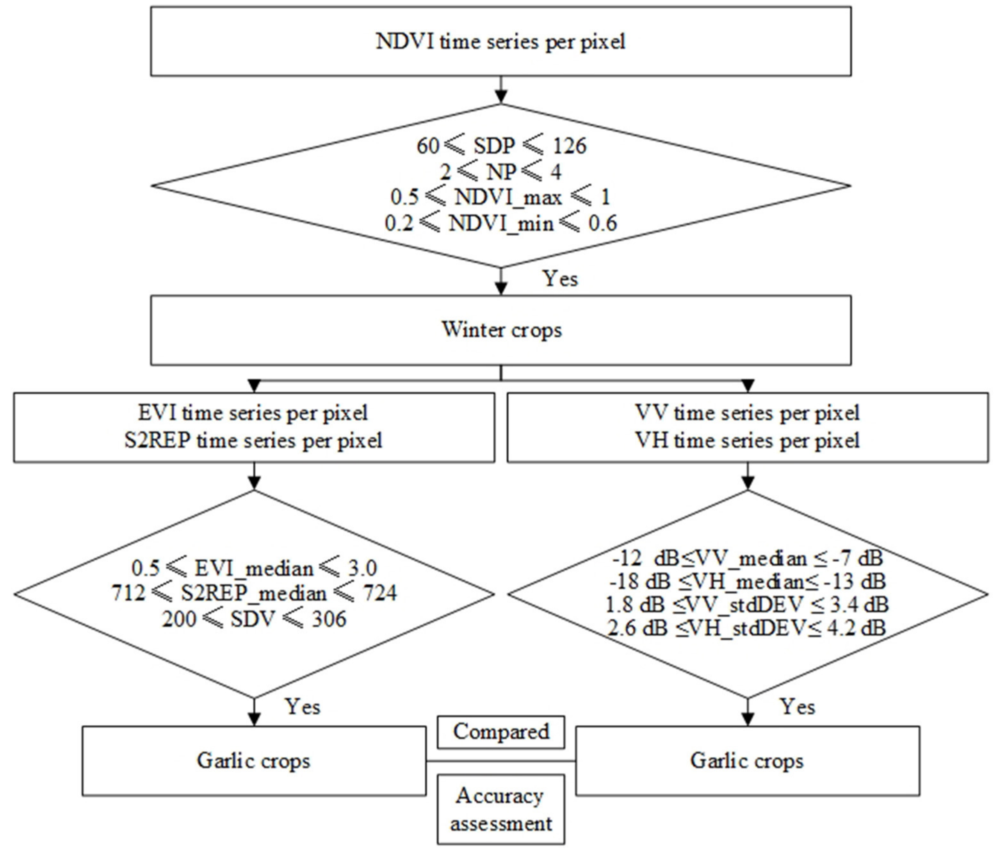

FIGURE 5
The algorithm framework for identifying garlic.

basis for identifying the garlic, and (2) identification of the garlic within the winter crop map. Specifically, we determined the winter crop field by monitoring phenological indices of winter crops recorded in the normalized difference vegetation index (NDVI) time series. Then, based on winter crop pixels, we mapped the garlic using time series from S2 and S1. Finally, we evaluated the performance of using optical images only and coupling optical images to SAR images in mapping the garlic.

Index calculation

Spectral indices that are sensitive to vegetation greenness can be used to capture the physical differences of different land cover types (Di Vittorio and Georgakakos, 2018) and characterize the growth curves of different crop types (Wardlow et al., 2007). NDVI (Tucker, 1979) and enhanced vegetation index (EVI) (Huete et al., 2002), which are highly related to leaf area index and chlorophyll in the canopy, are widely used in the remote sensing inversion of vegetation phenology. Sentinel-2 red-edge position index (S2REP) (Frampton et al., 2013) can effectively monitor the growth stages of vegetation (Forkuor et al., 2018) and shows higher performance in crop classification (Yi et al., 2020). The calculation formulas are as follows:

$$\text{NDVI} = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}}$$

$$\text{EVI} = 2.5 \times \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + 6.0\rho_{red} - 7.5\rho_{blue} + 1}$$

$$\text{S2REP} = 705 + 35 \times \frac{0.5 \times (\rho_{re3} + \rho_{red}) - \rho_{re1}}{\rho_{re2} - \rho_{re1}}$$

where the ρ_{nir}, ρ_{red}, and ρ_{blue} represent the NIR, red, and blue bands, respectively. ρ_{re1}, ρ_{re2}, and ρ_{re3} represent the RE1, RE2, and RE3 bands, respectively.

Time-series construction

Compositing images at regular intervals can reduce the impact of clouds and uneven observations in time (Griffiths et al., 2019). Therefore, the VIs time series were constructed at 10-day intervals. The maximum value of all good-quality observations within a 10-day period was taken as the observation value of the 10-day period. When there was no good-quality

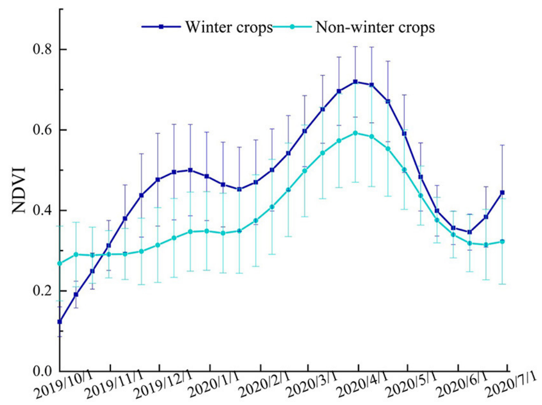

FIGURE 6
Temporal profile of average NDVI for winter crops and non-winter crops with standard deviation.

observation in a 10-day period due to clouds, cloud shadows, and snow effects, the linear interpolation method was used to fill the data gap. The interpolated data depends on good-quality observations before and after the 10-day interval. Further, VV, VH, and standard deviation time series were reconstructed at 12-day intervals. However, even after the above steps, extremely high or low outliers may still appear in the time series, which is usually caused by cloud containment, atmospheric variability, and bidirectional effects. Therefore, the Savitzky-Golay filter was used to smooth the time series with a moving window of size 9 and a filter order of 2 (Chen et al., 2018; Pan et al., 2021a).

Annual map of winter crops in 2020

Because garlic is a winter crop, winter crops were firstly extracted from the cropland. Compared with non-winter crops, the chlorophyll content of winter crops increased continuously after sowing and decreased slightly during the vernalization period (Figure 6, October 2019 to January 2020). Therefore, there was a lower peak in the NDVI time series of winter crops during this period (Figure 6). Non-winter crops were usually harvested or not sown during this period, so their NDVI was low.

According to these unique phenological characteristics of winter crops, the start date of peak (SDP), the number of peaks (NP), NDVI_max, and NDVI_min phenological indices were selected. Among them, SDP is the first peak identified from October 1, 2019, to July 1, 2020; NP is the number of peaks identified from October 1, 2019, to July 1, 2020; NDVI_max is the maximum value of NDVI time series from October 1, 2019, to January 1, 2020; and NDVI_min is the minimum value of NDVI time series from June 1, 2020, to July 1, 2020.

The training samples of winter crops and non-winter crops were overlaid with the four phenology index layers to carry out a signature analysis (Figure 7). The results showed that the SDP of winter crops occurs mostly in late October to late January [day of the year (DOY) from 60 to 126]. NP is 2–4. The NDVI_max mainly gathers between 0.5 and 1, and NDVI_min mainly gathers between 0.2 and 0.6. Based on the results of signature analysis, an algorithm was developed for winter crops:

$$60 \leq \text{SDP} \leq 126 \ \& \ 2 \leq \text{NP} \leq 4 \ \& \ 0.5 \leq \text{NDVI\_max} \leq 1 \ \& \ 0.2 \leq \text{NDVI\_min} \leq 0.6$$

The algorithm was applied to extract the winter crops in Qi County, and garlic mapping was performed from the winter crops.

Annual map of the garlic in 2020 based on optical images

The winter crops in Qi County were further divided into garlic and winter wheat. Although garlic and winter wheat were sown and harvested at almost the same time, the EVI and S2REP of garlic in the growth period (Figure 8, December 2019 to April 2020) were lower than those of winter wheat, and its harvest period was earlier than that of non-garlic winter crops.

According to these unique characteristics of garlic, the EVI_median, S2REP_median, and start date of the valley (SDV) phenological indices were extracted. Among them, EVI_median is the median value of EVI from December 1, 2019, to April 1, 2020; S2REP_median is the median value of S2REP from December 1, 2019, to April 1, 2020; and SDV is the first valley identified from May 1, 2020, to July 1, 2020.

The training samples of garlic and winter wheat were overlaid with the three phenology index layers to carry out a signature analysis (Figure 9). The results showed that the EVI_median of garlic mainly gathers between 0.5 and 3.0, and the S2REP_median mostly gathers between 712 and 724. The SDV of garlic gathers between 200 and 306. Based on the results of signature analysis, an algorithm was developed for identifying garlic:

$$0.5 \leq \text{EVI\_median} \leq 3.0 \ \& \ 712 \leq \text{S2REP\_median} \leq 724 \ \& \ 200 \leq \text{SDV} \leq 306$$

The algorithm was implemented to identify garlic over the winter crops generated in section annual map of winter crops in 2020.

Annual map of garlic in 2020 based on SAR images

The backscattering intensities of S1 images are sensitive to crop phenology and morphological development (Mandal et al., 2020), which provides an unprecedented opportunity for garlic monitoring. Unlike winter wheat, the distance between garlic

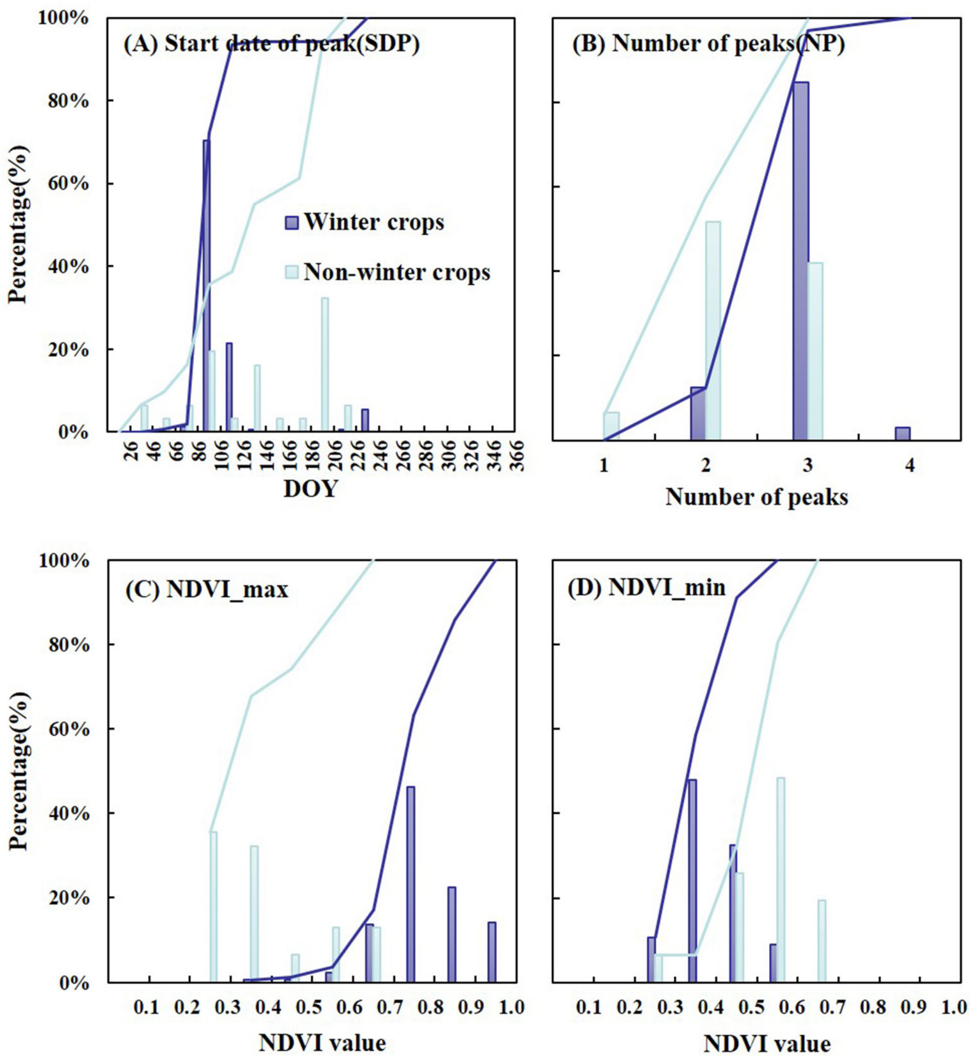

FIGURE 7
Signature analysis of winter crops and non-winter crops at **(A)** SDP, **(B)** NP, **(C)** NDVI_max, and **(D)** NDVI_min using the histogram statistics method.

plants is larger and therefore, the backscattering coefficient of garlic is higher than that of winter wheat (Figure 10).

According to these unique garlic characteristics, the VV_median, VH_median, the standard deviation of VV (VV_stdDEV), and the standard deviation of VH (VH_stdDEV) phenological indices were selected to extract the garlic. Among them, VV_median and VH_ median are the median values of VV and VH from March 1, 2020, to May 31, 2020, and VH_stdDEV and VH_stdDEV are the standard deviations of VV and VH from October 1, 2019, to July 1, 2020, respectively.

The training samples of the garlic and winter wheat were overlaid with the four phenology index layers to carry out a signature analysis (Figure 11). The results showed that the VV_median of the garlic mainly gathers between −12 and −7 dB, and VH_median mostly gathers between −18 dB and −13 dB. The VV_stdDEV of the garlic mainly gathers between 1.8 and 3.4 dB, and VV_stdDEV mostly gathers between 2.6 and 4.2 dB. Based on the results of signature analysis, an algorithm was developed for identifying the garlic:

$$
\begin{aligned}
-12\text{ dB} \leq \text{VV\_median} \leq -7\text{ dB} \ \& -18\text{ dB} \\
\leq \text{VH\_median} \leq -13\text{ dB} \ \& \ 1.8\text{ dB} \leq \text{VV\_stdDEV} \\
\leq 3.4\text{ dB} \ \& \ 2.6\text{ dB} \leq \text{VH\_stdDEV} \leq 4.2\text{ dB}
\end{aligned}
$$

The classification algorithm was implemented to identify the garlic based on the winter crop pixels.

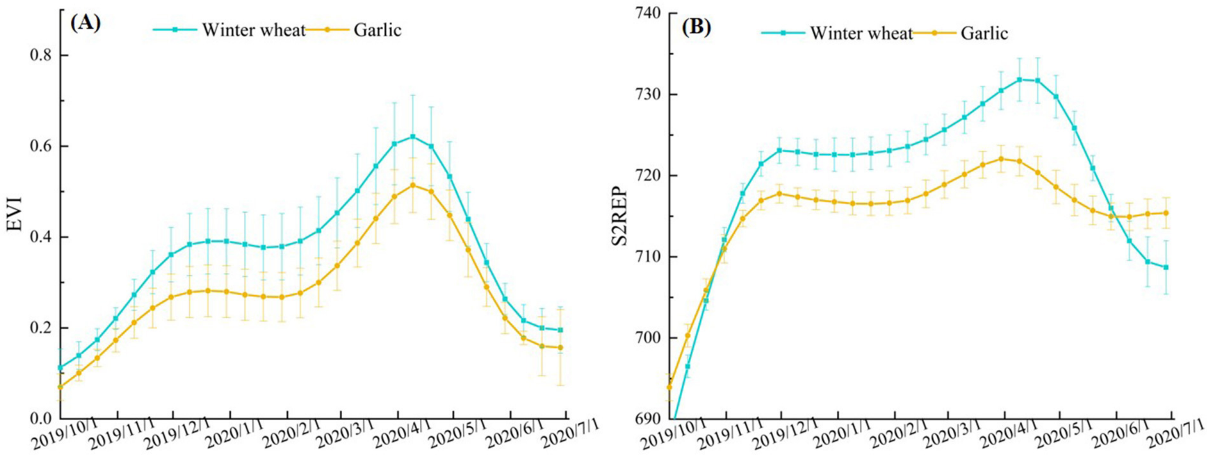

FIGURE 8
Temporal profile of average EVI **(A)** and S2REP **(B)** for winter wheat and garlic with standard deviation.

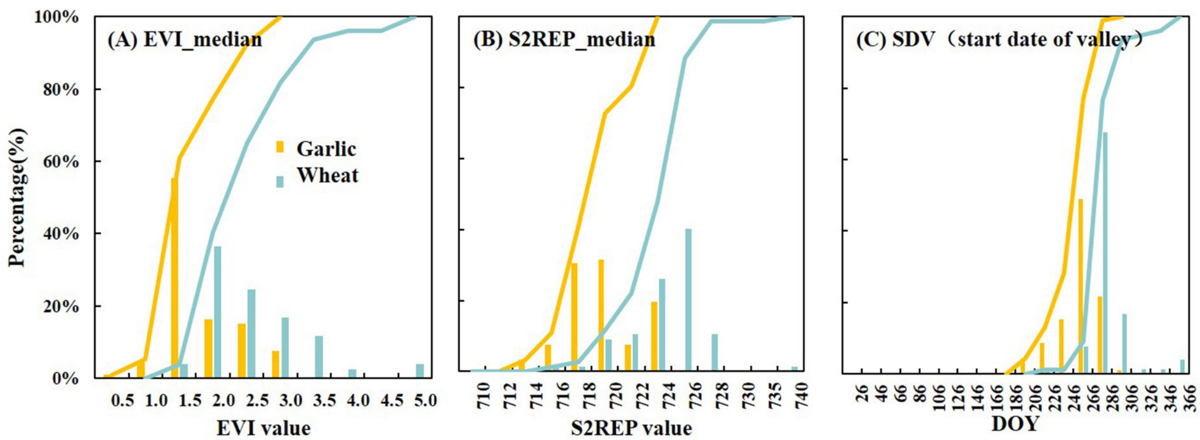

FIGURE 9
Signature analysis of garlic and winter wheat at **(A)** EVI_median, **(B)** S2REP_median, and **(C)** SDV using the histogram statistics method.

Accuracy assessment of the resultant annual maps

Confusion matrices were used to assess the accuracy of the winter crop and garlic distribution maps (Guo et al., 2021). It is a method to characterize the classification performance in terms of overall accuracy (OA), producer accuracy (PA), and user accuracy (UA) by constructing a matrix of classification results and sample data. It uses the following formulas,

$$OA = \frac{T_1 + T_2}{N} \quad (1)$$

$$PA = \frac{T_1}{T_1 + F_2} \quad (2)$$

$$UA = \frac{T_1}{T_1 + F_1} \quad (3)$$

where N is the total number of multi-classes, T_1 and T_2 are the numbers of correct classifications for class 1 and class 2, and F_1 and F_2 are the numbers of wrong classifications for class 1 and class 2, respectively. Firstly, the ground reference data obtained in section ground reference data were loaded into Google Earth, and the vector boundary of the homologous ground reference points was plotted according to the actual size and shape of the cropland. Secondly, the attributes of the vector polygons were labeled by visual interpretation and field survey data. A total of 412 garlic samples (30,658 pixels), 451 winter wheat samples (34,121 pixels), and 453 non-winter crops samples (65,112 pixels) were collected. Thirdly, these vector polygons with attribute information (e.g., the garlic, winter wheat, or non-winter crops) were converted into raster data with a spatial resolution of 10 m (Figure 12). These raster data were used as

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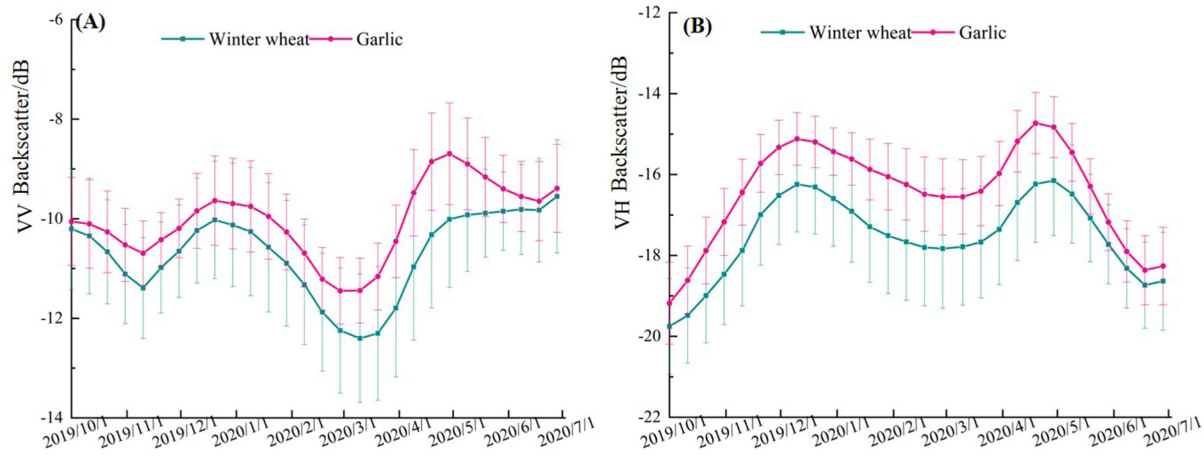

FIGURE 10
Temporal profile of average VV **(A)** and VH **(B)** for winter the wheat and garlic with standard deviation.

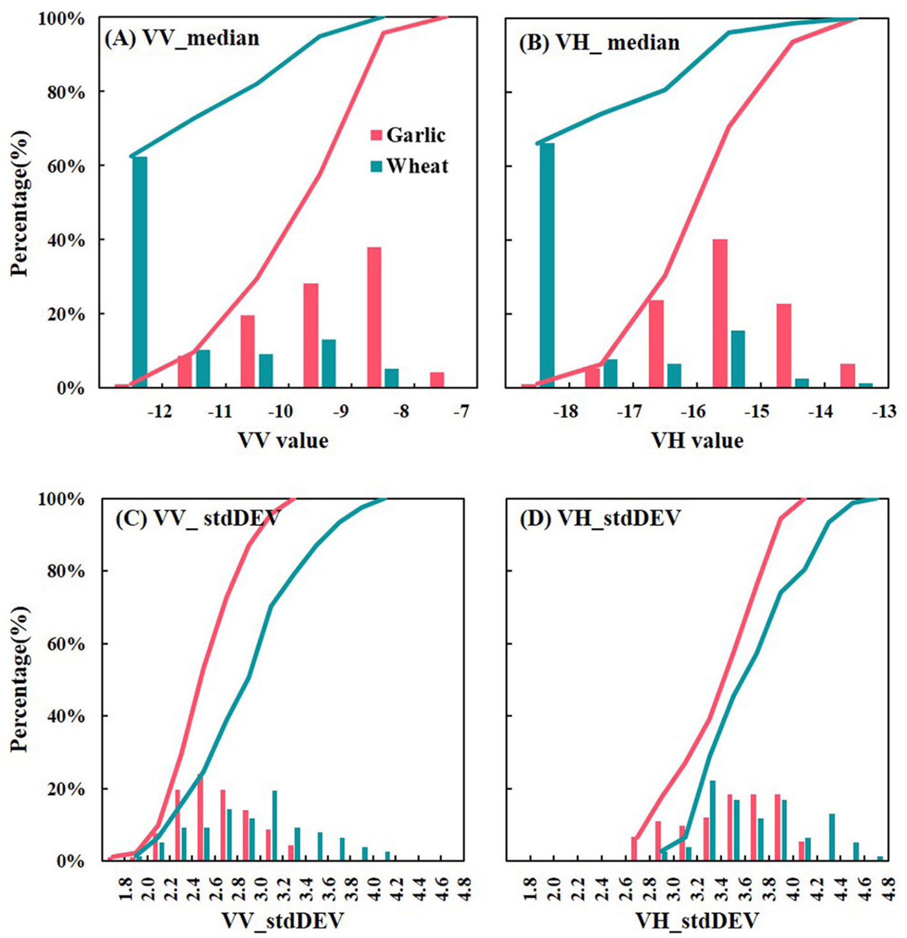

FIGURE 11
Signature analysis of garlic and winter wheat at **(A)** VV_median, **(B)** VH_median, **(C)** VV_stdDEV, and **(D)** VH_stdDEV using the histogram statistics method.

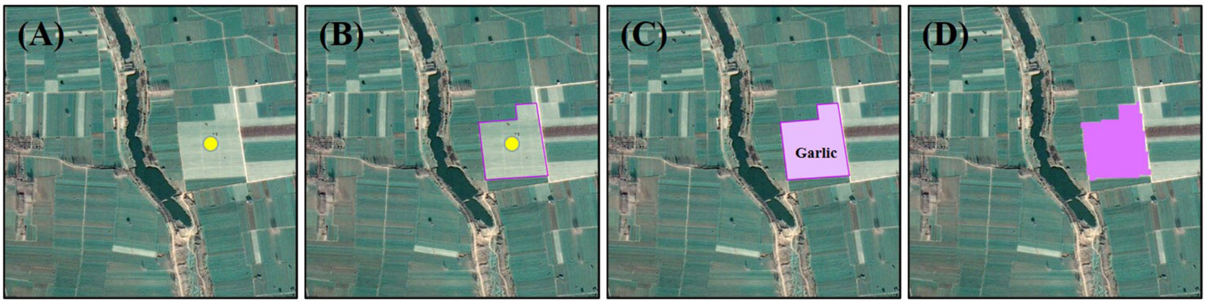

FIGURE 12
Flow diagram for validation data production. **(A)** The Google Earth image. **(B)** The results of vectorization, where the purple line is the garlic cropland boundary. **(C)** The results for identifying the attributes of the vector polygon. **(D)** The raster converted from the vector polygon.

ground reference data to construct the confusion matrix with the classification results in this paper.

Results

Annual map of winter crops in 2020

Figure 13 shows the distribution of winter crops with a 10-m resolution across Qi County in 2020. There were 1062.27 km^2 of winter crop fields in Qi County in 2020, accounting for 74.81% of the total cropland area. Four regions were randomly selected. In region b, the main winter crop type was winter wheat, and the main non-winter crop type was spring maize. There was a forest farm in Qi County in region c. Most cropland here was planted with trees and only a small part of the cropland was planted with garlic. In regions d and e, the main winter crop type was garlic, while spring peanuts were planted in small fields.

Annual map of garlic in 2020

As described in sections annual map of the garlic in 2020 based on optical images and annual map of garlic in 2020 based on SAR images, the distribution of garlic in 2020 was identified by analyzing phenological indices from October 2019 to October 2020. Annual maps of garlic in 2020 with a 10-m resolution were produced (Figure 14). As per Figures 14A,B, there were 624.95 km^2 and 658.98 km^2 of garlic fields in Qi County in 2020, which accounted for 58.83 and 62.04% of winter crop fields, respectively. Four regions were randomly selected to compare the resultant annual map obtained using the two datasets. In the garlic distribution map based on S2 (Figures 14C2,D2,E2,F2), there was a great loss of cropland boundary information, and the commission and omission of the garlic fields were more serious. In the garlic distribution map based on S1 (Figures 14C3,D3,E3,F3), the cropland boundary information was relatively complete. Small garlic fields and non-garlic crop fields in the staggered distribution zone of cropland and villages were well-identified, and the classification results were better.

Accuracy assessment of the resultant annual maps

Based on the raster data obtained in section accuracy assessment of the resultant annual maps, the accuracy assessment results using the confusion matrix are shown in Table 1. The OA, UA, and PA of the winter crops distribution map were 98.07, 96.02, and 99.30%, respectively. The kappa coefficient was 0.96, which indicated a strong consistency between the classification results and the ground reference data. The accuracy assessment results showed that the algorithm proposed in this study successfully extracts the winter crop pixels in Qi County in 2020, which lays a foundation for the recognition of garlic.

Furthermore, the confusion matrix was calculated using the garlic and non-garlic crop raster data obtained in section accuracy assessment of the resultant annual maps (Tables 2, 3). The OA, UA, PA, and kappa coefficient of the garlic distribution map based on S2 were 74.78%, 69.61%, 79.93%, and 0.50, respectively, while those based on S2 and S1 were 95.34%, 95.33%, 95.79%, and 0.91, respectively. Comparing the accuracy assessment results of the two algorithms, the garlic extraction algorithm based on S1 had higher accuracy and stronger consistency with the ground reference data.

Discussion

Integration of times series S1 and S2 images

Crops have unique spectral characteristics that make optical images an important data source for remote sensing crop

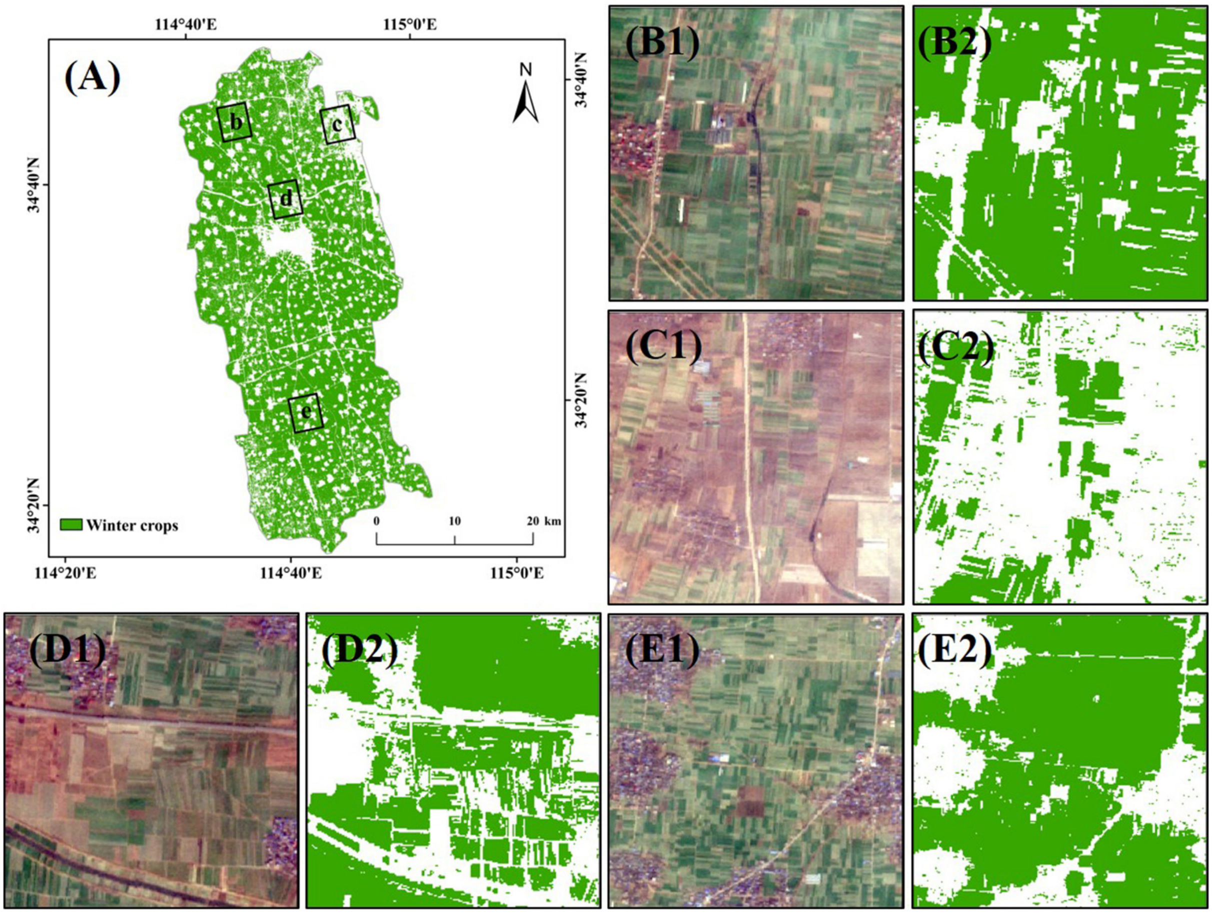

FIGURE 13
(A) Distribution of winter crops in Qi County in 2020. Four regions, denoted as b, c, d, and e in **(A)**, were randomly selected. The 10-m resolution views from Sentinel-2 (December 19, 2019) are shown in **(B1,C1,D1,E1)**, and the zoom-in views in **(A)** for the four regions are shown in **(B2,C2,D2,E2)**.

recognition (Liu et al., 2017; Pan et al., 2021b). Therefore, winter crops were extracted from cropland based on S2 optical images. Compared with previous studies using MODIS images or Landsat images to extract winter crops (Pan et al., 2021b), the results provided a higher spatial resolution of 10 m. However, optical images have some limitations in distinguishing various crop types. First, the number of available optical images is often affected by clouds, cloud shadows, and snow (Ju and Roy, 2008), so good-quality images vary greatly in time and space. Although we attempted to extract the garlic using spectral differences at specific growth stages, the accuracy assessment results were not satisfactory (Table 2).

The S1 SAR images provide an opportunity to distinguish garlic from non-garlic winter crops. As shown in Figure 10, winter wheat was usually in the elongation and booting stage around April. The number and length of stems increased significantly during this period, which led to changes in the winter wheat's 3D structure. This was the main reason for the decrease in the backscattering coefficient of winter wheat (Jia et al., 2013), while garlic did not show these changes. The classification effects of various indices that have been used to develop a decision rule for classification analysis were compared, and the indices with the best separability were selected (Supplementary Figure 1). The results show that this study provides useful data for identifying garlic by remote sensing.

Algorithm development and applications

In previous studies, VIs have been used to generate garlic distribution maps (Guo et al., 2022b), but natural and human factors may lead to certain deviations in these indices. Figure 8A showed that the EVI of garlic was lower than that of winter wheat from December to April, which may be one of the indices to distinguish the garlic. However, farmers usually increase the planting density of garlic to increase the planting income,

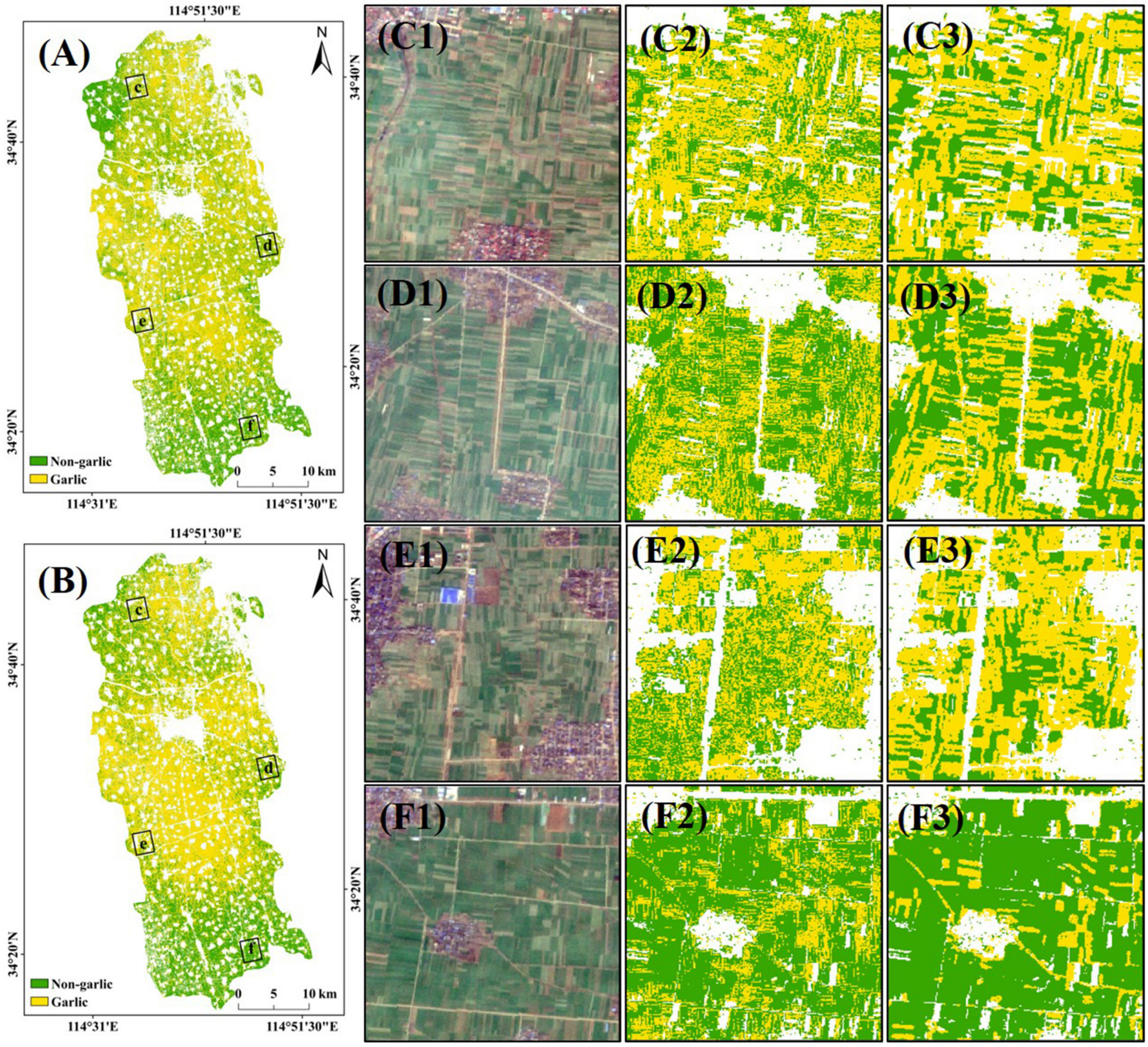

FIGURE 14
(A) Distribution of garlic in Qi County in 2020 only based on S2. **(B)** Distribution of garlic in Qi County in 2020 based on S2 and S1. Four regions, denoted as c, d, e, and f in **(A,B)**, were selected randomly. The 10-m resolution views from Sentinel-2 (December 19, 2019) are shown in **(C1,D1,E1,F1)**, and the zoom-in views in **(A,B)** for the four regions are shown in **(C2,D2,E2,F2,C3,D3,E3,F3)**.

TABLE 1 Results of accuracy validation for the winter crops.

Class	Error matrix (Pixels)			Accuracy (%)			Kappa
	Winter crops	Non-winter crops	Total	User's	Producer's	Overall	
Winter crops	47305	333	47638	96.02	99.30	98.07	0.96
Non-winter crops	1871	64779	66650	99.49	97.19		
Total	49176	65112	114288	/	/	/	/

which may increase the EVI of garlic and could cause the similar EVIs of garlic and winter wheat. Although the harvest time of garlic is earlier than that of winter wheat, the 10-day resolution makes it difficult for S2 images to capture this information on a large scale. Additionally, clouds, rain, and snow may cause the fluctuation of EVI and S2REP time series, which may lead to the overlap in the VI time series of garlic and winter wheat. Therefore, it is difficult to accurately

TABLE 2 Results of accuracy validation for the garlic crop based on Sentinel-2.

Class	Error matrix (Pixels)			Accuracy (%)			Kappa
	Winter wheat	Garlic	Total	User's	Producer's	Overall	
Winter wheat	23750	5965	29715	69.61	79.93	74.78	0.50
Garlic	10371	24693	35064	80.54	70.42		
Total	34121	30658	64779	/	/	/	/

TABLE 3 Results of accuracy validation for the garlic crop based on Sentinel-2 and Sentinel-1.

Class	Error matrix (Pixels)			Accuracy (%)			Kappa
	Winter wheat	Garlic	Total	User's	Producer's	Overall	
Winter wheat	32529	1429	33958	95.33	95.79	95.34	0.91
Garlic	1592	29229	30821	95.34	94.83		
Total	34121	30658	64779	/	/	/	/

distinguish garlic and winter wheat only based on S2 data. Some studies have input the characteristics of the garlic backscattering coefficient in a specific time window into the RF classifier to extract the garlic. However, the time windows of crops with different spatial distributions vary greatly, and it is difficult to determine accurate time windows. Moreover, complex feature combinations and indices may also cause the model to overfit (Graesser and Ramankutty, 2017).

In this study, the complete growth cycle of the garlic was monitored for 1 year and several phenological indices were extracted based on the unique phenological characteristics of garlic in different growth periods. Using these phenological indices, the classification rules were established for garlic. Only pixels that meet these classification rules could be identified as garlic. Compared with other methods, the proposed algorithm simulates the growth of the garlic more realistically (Supplementary Figure 2). Furthermore, this study only took 2020 as an example of mapping the garlic distribution in Qi County. The Sentinel satellite database of the past few years is provided free of charge on the GEE cloud platform. Therefore, the algorithm can also generate garlic distribution maps from other years or regions based on these images (Supplementary Figure 3). This is because relatively consistent environmental factors such as planting mode, management mode, and climate may make garlic grow in the same cropland for many years. It is worth noting that S2 TOA data was used in the garlic distribution map in 2019 (Supplementary Figure 3), as S2 SR data for the study area over the entire 2019 were not available on the Google Earth Engine (GEE) platform. However, TOA data may lead to greater errors (Supplementary Figures 4, 5). Additionally, the algorithm proposed in this study can also generate distribution maps of other crop types by adjusting the classification indices and their threshold using local training samples.

Potential sources of uncertainty

Several factors may affect the classification results of this study. First, reliable land cover data is an important factor to improve the accuracy of the garlic distribution map. The FROM-GLC10 land cover product was used with a 10-m resolution to distinguish cropland from other land types. However, there were some classification errors in this product, especially for the staggered distribution zone of cropland and villages (Figure 12). Additionally, the product reflects the land cover in 2017, which is inconsistent with that of the study year (2020). These errors are easily propagated to the final garlic distribution map output. The publication of more reliable land cover data is expected to further improve the accuracy of the research results.

Second, for the missing values in the VI time series, linear interpolation was used based on neighboring pixels. When good-quality observations are missing at the peaks (valleys), the interpolation cannot reflect the real positions of crop growth (Guo et al., 2021). Third, in the process of extracting winter crops, the NDVI < 0.6 was used from June 2020 to July 2020 as one of the classification indices. However, there were mixed pixels of deciduous forest and winter crops on both sides of the road through fieldwork. The deciduous forest has lush branches and leaves and high chlorophyll content from June to July, which may lead to the NDVI > 0.6 of the mixed pixels. Finally, winter crops include winter wheat, winter canola, and winter vegetables, and the differences between them were not discussed in this study. A comprehensive analysis of image characteristics of different types of winter crops and improving the universality of the algorithm proposed in this study are warranted in further research.

Conclusion

In this study, an automatic mapping framework was proposed to identify and map the garlic distribution using time series optical images (Sentinel-2) and microwave images (Sentinel-1). The NDVI time series dataset was obtained from Sentinel-2 images and used to map winter crop distribution. Garlic was identified by Sentinel-2 (EVI and S2REP) and Sentinel-1 (VV, VH, and the standard deviation of VV and VH) images. Using the algorithm framework, the distribution maps of winter crops and garlic in Qi County in 2020 were generated with a 10-m resolution. The OA of the winter crop distribution map was 98.07%, with a Kappa coefficient of 0.96, laying a foundation for the recognition of garlic. The OAs of the garlic distribution map based on S2 and S1 were 74.78 and 95.34%, and the kappa coefficients were 0.50 and 0.91, respectively. The garlic distribution map obtained in this study could help stakeholders optimize the garlic planting systems for sustainable garlic production.

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

YC: data collection, writing—original draft, and writing–review and editing. YG: formal analysis, writing–original draft, and writing–review and editing. LQ: resources and validation. HX: conceptualization, resources, writing–review and editing, project administration, and funding acquisition. All authors contributed to the article and approved the submitted version.

Conflict of interest

Author YC was employed by Yankuang Donghua Construction Co., Ltd.

The remaining 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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1007568/full#supplementary-material

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The role of renewable energy in achieving water, energy, and food security under climate change constraints in South Asia

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The energy demand in South Asia is increasing at a rapid rate and it is becoming harder to meet the demand due to the high cost of conventional energy sources, the unsustainability of energy use, and the high emissions caused by the energies. South Asia is blessed with a high potential for renewable energy, especially hydropower, but that has not been adequately tapped. This has highly compromised the food, water, and energy security of the people in South Asian countries. This article identifies the roles of renewable energy sources in achieving energy, water, and food security for South Asian nations and provides suggestions for enhancing the utilization of renewable resources. The article identifies the potential for the promotion of hydropower and other renewable energy sources as well as opportunities and potential challenges for multilateral energy trade for increasing the availability of energy. It also recommends possible solutions and approaches for the promotion of hydropower and other renewables in South Asia. The article infers that a nexus approach for integrated planning, policy coherence, and institutional harmonization increases the benefit by reducing transaction costs, generating additional synergies, and reducing the trade-off at different scales. These approaches enhance energy, food, and water security, and eventually improve the quality of life in the region. Improved access to renewable energy can contribute directly and indirectly to achieving Sustainable Development Goals (SDGs) in this region.

KEYWORDS
renewable energy, hydropower, water-energy-food nexus, climate change, South Asia

Introduction

South Asia is home to 1.75 billion people which is almost one-fifth global population living within an area of 5,134,641 km^2, i.e., 23% of the world's land (Rasul, 2014). Approximately half of the world's poor and slightly more than one-third of the world's undernourished people live in South Asia. Per capita energy consumption is among the lowest in the region. About 417 million people (24%) lack access to electricity and 60% of the total population depend on biomass for cooking and heating (Rasul, 2014)[1,2]. About 20% of the population lack access to safe drinking water (Rasul, 2014) and 60% of the population lack access to improved sanitation (WHO/UNICEF Joint Water Supply Sanitation Monitoring Programme, 2014). Energy demand is increasing at 7.4% per year (Hydro Status Report, 2017) due to the growing population and rapid economic transformation. The energy and water demand of India and the cereal demand of the entirety of south Asia are expected to double by 2035 (Rasul, 2014; EIA, 2018).

Meeting energy demand in South Asia from conventional energy sources is expensive and unsustainable; it contributes to higher emissions and global warming. About 80% of the commercial energy mixture in South Asia comes from fossil fuels and hydropower contributes <6% to commercial energy (Tortajada and Saklani, 2018). The use of coal in South Asia is expected to grow from 2 to 27.6% in 2030, as coal is the main indigenous energy source in Pakistan and Bangladesh (see text footnote 2). Nepal alone imported fuel of Rs 214.48 billion in 2020 which is nearly 15% of Nepal's total budget in that fiscal year.

Figure 1 depicts the trend of three different sources of irrigation over a period of half-century starting from 1950 in South Asia. The figure clearly shows the exponential growth in the use of groundwater over the fifty years, which implies that the insecurity in energy imposes a threat to water and food security globally and in South Asian nations in particular. Considering the upstream-downstream interdependency in this region, energy, water, and food challenges remain crucial. Unfortunately, no country in South Asia is energy sufficient. More than 30% of energy demand is satisfied through imports in this region. The share of imported energy to total primary energy use (excluding biomass energy) is 86.3% for Nepal, 56.7% for Bhutan, 43.3% for India, and 26.3% for Bangladesh (Tortajada and Saklani, 2018). Currently, 60% of GHG emissions come from energy in India. India's energy-related CO_2 emission was 573 MTOE in 1990 and it increased to 1,566 MTOE in 2015, a 173% point increment in the total global emissions (EIA, 2018)[3]. CO_2 emission in India is increasing at 1.8% annually compared to 1.3% global growth rates (see text footnote 3; EIA, 2018). On the other hand, higher dependency on biomass and fossil fuel contributes to higher emissions and global warming.

The South Asian region is very rich in freshwater resources since it is interconnected by the Transboundary River system of the Ganges, Brahmaputra, Meghna, and Indus. As the riparian countries in those river basin systems, there is a strong upstream-downstream linkage among Afghanistan, Pakistan, India, Bangladesh, Nepal, and Bhutan. The upstream countries provide freshwater to the downstream countries for irrigation, domestic use, flood regulation, and drought mitigation, while the downstream areas supply food and feed to the living beings in the upstream areas. Agriculture downstream depends on upstream water sources.

The upstream areas have locational advantages for multipurpose hydro-dams because of their comparatively low population density and hence lower domestic demand. The surplus can be traded to downstream countries which can be a good source of revenue for the upstream countries. Hydropower is non-consumptive water use and thus it is advantageous from an economic perspective to let each cubic meter flow through as many hydropower generation facilities as possible before it is withdrawn for consumptive use, such as agriculture. For example, a cubic meter of water flowing through the Himalayan rivers from upstream Nepal to India and then to Bangladesh can generate hydropower at different dam sites in Nepal and also add irrigation values to the farmers living downstream in India and Bangladesh on its way to the Bay of Bengal. The importance of upstream-downstream interdependence and the value of regional cooperation for optimal hydropower development and regional electricity trade of resources have not yet been fully appreciated in this region.

Hydropower is only the renewable energy in this region that is commercially viable on a large scale. It is an important source of power to resolve energy-water and food challenges (World Bank, 2014), and can also be a gateway for the economic development of the region. This region has an estimated 388 GW of hydropower potential; to date, only 16% has been tapped. Nepal, Afghanistan, and Bhutan have the lowest hydropower exploitation rate. Nepal alone has a hydropower potential of 83,000 MW, and it has only developed <2% of technically feasible hydropower capacity. Even if the energy demand of Nepal increases at a rate of 10% annually, domestic demand will reach only 3,679 MW by 2027 (Bergner, 2013), which is only 8% of the technically feasible hydropower potential and 4% of the theoretical potential. This presents an immense opportunity for the hydro-rich country such as Nepal in terms of energy trade, which will also help enhance the energy security of the South Asian region (Rahaman, 2012).

Operationalization of the energy-water-agriculture nexus would help find the solution for energy, water, and food security issues in South Asia. The nexus approach helps bring policy coherence and institutional harmonization at cross-sectors and cross-country levels. Nexus is a universal principle but issues differ with the different resource endowments. In the South Asian context, water availability and yield improvement are possible through improvement in energy access. Here, nexus

1 International Energy Agency (IEA) (2018). Available online at: http://www.iea.org/statistics/.

2 World Bank (2018). Available online at: https://data.worldbank.org/.

3 World Energy Outlook (2017). Available online at: https://www.iea.org/weo2017/.

has to be looked into from an energy perspective because energy is central to water and food security and climate change adaptations. The UN Sustainable Development Goals (SDGs) have stressed that access to modern energy is a requisite for achieving Sustainable Development Goals (UNDP, 2013) and is also considered the best adoption option for climate change. This is the current policy focus of South Asian countries. For instance, during COP 21 in Paris on Intended Nationally Determined Contributions (INDCs), India committed to reducing 33–35% of greenhouse gas emissions by 2030. This commitment is considered the game-changer of the energy mix of all of South Asia to switch to a more sustainable mode of energy which is only possible through improvement in energy trade in the region. It will help increase energy availability, change the current fossil-fuel-dominated energy mixture to clean energy, and most importantly the hydro-rich countries will generate substantial revenue through electricity exports. A World Bank study shows this region can save up to US$226 billion during 2015–2040 at the rate of US$9 billion per year by adding only 95 GW energy (only 25% of the total potential) if there is the provision of unrestricted cross-border trade (Timilsina and Toman, 2016).

This article aims to present energy, water, and food security in the South Asian context from a nexus perspective, where the untapped potential of renewable energy, particularly hydropower can play a vital role in improving the nexus. It shows the major challenges of the slow growth of renewable energy and suggests nexus-focused solutions for overall national improvement.

Challenges of energy, water, and food security in South Asia

South Asia suffers from energy security which has a direct linkage with food and water security. Climate change further exacerbates energy, water, and food security. This section describes the issue of energy security in South Asia that affects food and water security differently and how climate change further impacts the nexus.

Energy security

The major source of energy for the population of South Asia is biomass, followed by oil, gas, coal, and electricity. Approximately, 65% of the total population relies on the biomass of mostly wood, crop residues, and animal dung. This dependency on biomass is not only inefficient but also has severe health and environmental consequences. South Asia's commercial energy mix is composed of 50% coal, 29% petroleum, 13% natural gas, 5% hydroelectricity, 1% nuclear energy, and 17% renewables (see text footnote 2). But the contribution of clean energy, which mostly consists of hydropower, is very minimal; it is only 6%.

Fossil fuel is the main source of commercial energy in most South Asian nations. Fossil fuel is considered an unsustainable and unpredictable source of energy with higher emissions and, additionally, its supply is subject to price volatility. Even though India and Pakistan have the largest technically feasible hydropower source in South Asia, the electricity generation in these nations is not only predominantly based on fossil fuels but also shows an increasing trend in harvesting electricity from fossil fuels (Tortajada and Saklani, 2018) This trend has been reflected in some of the other South Asian nations as well.

By sector, in South Asia, the industrial sector is the most energy-intensive area which consumes 45% of the total energy supply, followed by domestic use (25.1%), transportation (13.5%), commercial and public services (3.7%), agriculture/forestry (2.5%), other non-specified (1.3%), and non-energy use (9.2%) (see text footnote 2). As the industrial sector is the most energy-intensive area, the impacts of economic growth, growing population, and climate change will demand more energy in the future. The expansion of industrial sectors in South Asia has elevated economic growth and livelihood, while the GHGs generated from this sector also aggravated the impacts of climate change in the region.

Figure 2 depicts the per-capita energy consumption in South Asian countries which is almost negligible in comparison to a developed country, for example, Iceland, which has the highest per-capita energy consumption. It shows there is a higher gap and energy demand in this region is expected to increase exponentially with the pace of their economic growth. For instance, energy use in India has doubled since 2000 and 80% of its demand is still fulfilled by coal [International Energy Agency (IEA), 2021]. Low per-capita energy consumption and higher dependency on biomass and fossil fuel reflect energy insecurity and energy poverty in South Asia. Per-capita energy consumption is strongly correlated with food and water security and the overall economic development of the region. Considering the growing economic growth and increasing population and climate change impacts, it is expected to shrink further in the future.

Electricity access is another important dimension of energy security. This is also very poor in South Asia. Figure 3 depicts the population access of electricity to the percentage of national population in south Asia.

Over 376 million population in the six South Asian countries are deprived of electricity. Access to the electricity grid, reliability, regularity, adequacy, and quality energy supply in South Asia is very poor. The access to electricity in rural areas is even worse in South Asian countries even though the rural areas need quality energy supply for transportation, to improve agricultural productivity, and to bring new opportunities for generating income (Practical Action Nepal: Annual Report, 2010).

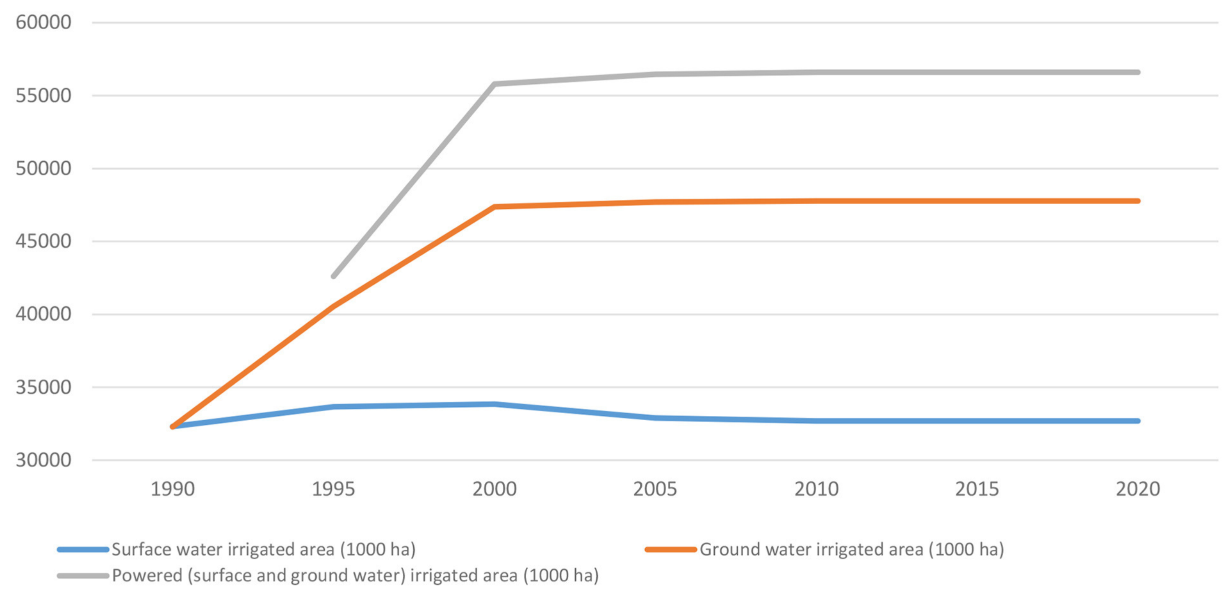

FIGURE 1
Trend of use of different sources of water for irrigation in South Asia from 1990 to 2020 (AQUASTAT, 2020).

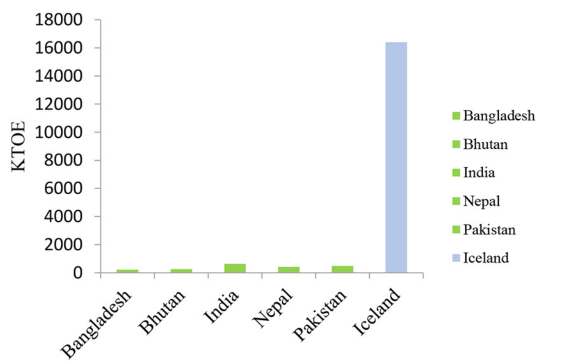

FIGURE 2
Per-capita Energy Consumption (PCEC) of SA nation compared to the nation with the world's largest PCEC (see text footnote 2).

Energy and water linkage

Energy security and water security have a two-way relationship as energy insecurity results in water insecurity and vice versa. Growing energy insecurity in this region impacts water security because energy is required to improve water availability and access.

More than half of the population that suffers from acute water scarcity lives in South Asia. Figure 4 elucidates the total percentage of drought effected area and there respective drought effected agricultural area; this is about 180 million in India and 73 million in Pakistan (Mekonnen and Hoekstra, 2016). Approximately 20% of the population lives without access to safe drinking water in South Asia (Rasul, 2014). The two largest countries of South Asia, India, and Pakistan are already water-stressed and water demand is predicted to increase by 55% by 2030 in South Asia (Rasul, 2014, 2016).

Out of 270 million ha of cultivated land in this region, 55% of the land still depends on rainwater for irrigation whereas, 45% of the land relies on an artificial irrigation system. Out of the total land with irrigation facilities, more than 55% of the land is groundwater-dependent. The production from this land contributes to 70–80% of the food demand (Rasul, 2014, 2016). Approximately 70–75% of the irrigated land in Bangladesh is fed by groundwater (Shahid, 2011) which was almost negligible during the 1960s. In India, Bangladesh, and Pakistan, groundwater is mostly used for domestic and agricultural use, which is energy-dependent. In many parts of India and Pakistan, groundwater extraction exceeding the recharge limit has resulted in its depletion. Approximately 6% of the national emission comes from groundwater withdrawal in India (Schröter, 2013). There is an estimated 26 million groundwater pumps for irrigation. Replacing only 5 million diesel pumps with electric pumps in India could save nearly 10 billion liters of diesel annually and several tons of emissions (Shah and Kishore, 2012).

Hydroelectricity generated as renewable energy has been recognized as a vital energy source in South Asia to cushion the emission generated from the industrial sectors. Since agriculture is a major source of economy in South Asia, agro-based industries such as dairy, cotton, sugar mills, fisheries, and brewery industries are growing at a faster pace, and reducing emissions by shifting from fossil fuels to renewable energy sources like hydroelectricity would help mitigation efforts to

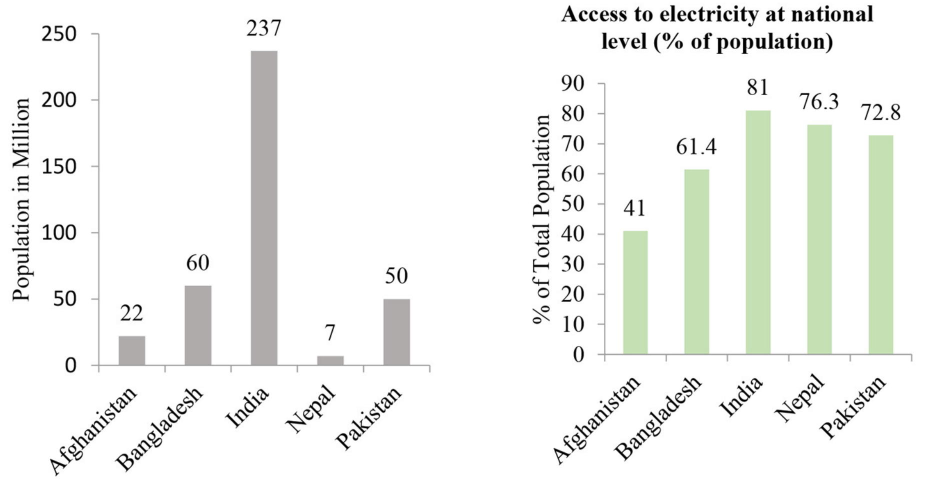

FIGURE 3
Population with electricity access.

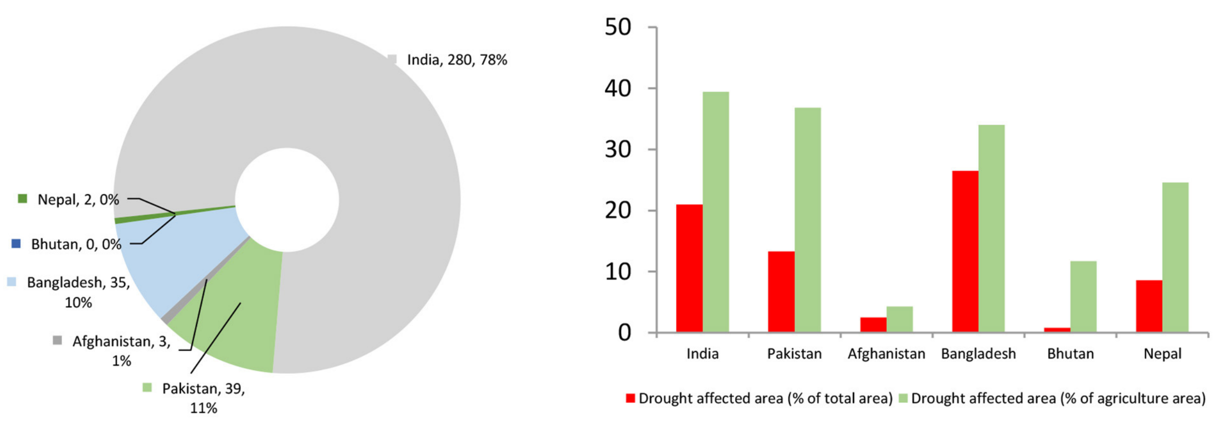

FIGURE 4
Population per million and agricultural land affected by drought.

climate change and contributes to the sustainable development in the region. Moreover, shifting to electric vehicles in the transport sector and access to cleaner energy sources in all the domestic, commercial and public sectors would help lessen the GHG emissions in South Asia. The practice of using indigenous knowledge in the region such as running water mills for small industries could be promoted as it demonstrates the nexus of water-energy and food under the changing climate.

Energy and food linkage

Energy is vital for food production, agriculture intensification, food transportation, and food price stabilization. Due to the rapid population growth, the per capita land availability in South Asia is decreasing. Per capita land availability in south Asia has dropped by almost four times within half a century (1960–2013) (see text footnote 2). By 2050, the population of South Asia is expected to reach 2.3 billion, and 65 % of this population will be urban. Accordingly, cereal demand is expected to double during the same time. On the other hand, due to urbanization and an increase in incomes, there is a significant move from starch-based diets toward more protein-based diets such as meat and dairy, which are more energy and water-intensive.

Currently, the use of energy in the agriculture sector is <5% in South Asia (Figure 5). The energy used in the agricultural sector is mostly fossil fuel-based which is used for farm mechanization, agrichemicals, and transportation. The portion of energy shared by South Asian nations in agriculture is far less

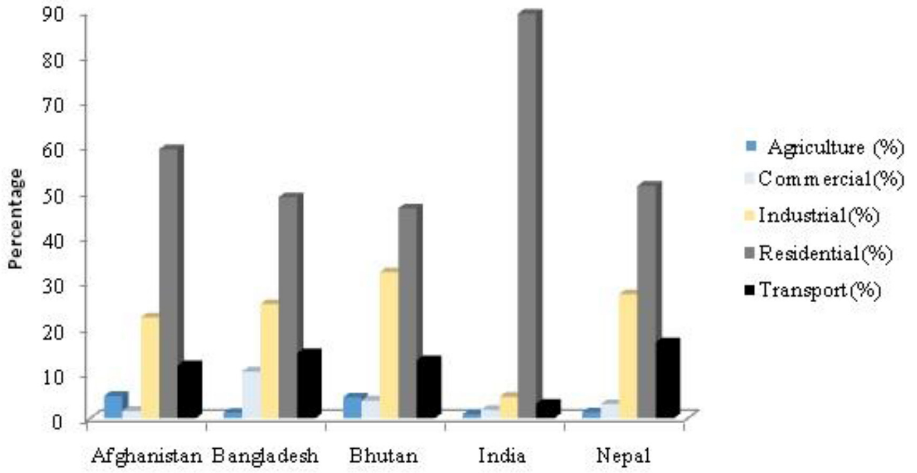

FIGURE 5
Energy consumption by different sectors in 2016.

when compared to that of developed nations. More than 55% of water in irrigated agriculture comes from groundwater in South Asia (Rasul, 2014) which requires energy. Most of the pumps in South Asia use fuel as a source of energy. In India alone, agricultural pumping accounts for $1/3^{rd}$ of the total energy consumption, which mostly comes from fossil fuels (Kumar, 2005).

Similarly, the production of fertilizers and agrochemicals requires a huge amount of energy. About 40 GJ of energy is required to produce one ton of Ammonia. The use of agrochemicals in agriculture results in Methane (CH_4) and Nitrous Oxide (N_2O) emissions. Looking at the aggregate figure in agriculture, for example, the total commercial energy input to Indian agriculture has increased from 425.4 × 109 Mega Joules (MJ) in 1980–81 to 2592.8 × 109 MJ in 2006-07. The consumption of energy per hectare of the net sown area has increased from 3 to 18.5 thousand MJ during this period (Surendra et al., 2011).

Increases in oil prices impact all aspects of commercial food systems. For example, between 2007 and 2008, world oil prices dramatically increased to US$150 per barrel, which was considered a major driver for increases in food prices. This has added millions of food-insecure people in the developing world (AQUASTAT, 2020). At present, the production of biofuels in South Asia is very modest, but might increase as a result of rising energy prices. This will increase competition for land and water resources for food or fuel production in South Asia, which is struggling for both food and energy security (De Fraiture and Wichelns, 2010). The increase in biofuel production in agricultural land in South Asia may increase energy production to some extent, but directly compete with food security as per capita land availability in South Asia is already very low in comparison to the global average.

Climate change impacts on energy

Climate change and extreme events alter water availability which ultimately imposes impacts on energy generation. On the other hand, higher dependency on biomass and fossil fuel contributes to higher emissions and results in global warming and climate change. There exists a two-way relationship between climate change and energy. Water availability is highly vulnerable to climate change. Rising temperature accelerates glacial melting and increases evapotranspiration, erratic rainfall, and droughts.

The mountains of the Hindu Kush Himalayan (HKH) region, the water tower of Asia, are warming significantly faster than the global average. By 2050, the temperature in the HKH region is predicted to increase by 1–2°C on average. In mountainous and high-altitude areas, temperature increases of 4–5°C result in faster shrinkage of the snow cover and glaciers (Shrestha and Aryal, 2011). Snow and glacier contribute more than 10% of annual discharge in the Nepalese river basin (Andermann et al., 2012). Glacier meltwater accounts for 10–15% of dry season flow in the Ganges (DFID, 2008). In the Budi Gandaki basin in Nepal, for example, glacier contribution to the total measured streamflow is about 30% (Jeuland et al., 2013). The disappearance of mountain glaciers in this region will have a significant impact on water resources, energy production, agriculture, and other uses. It is estimated that there will be a 3% average reduction in hydropower supply in Nepal, 2.7% in India, and 3.5% in Bangladesh by 2050 (Turner et al., 2017) due to climate change.

Increasingly intense flood events and glacial lake outbursts can cause severe harm to power production infrastructure and can result in more frequent blackouts in regions where

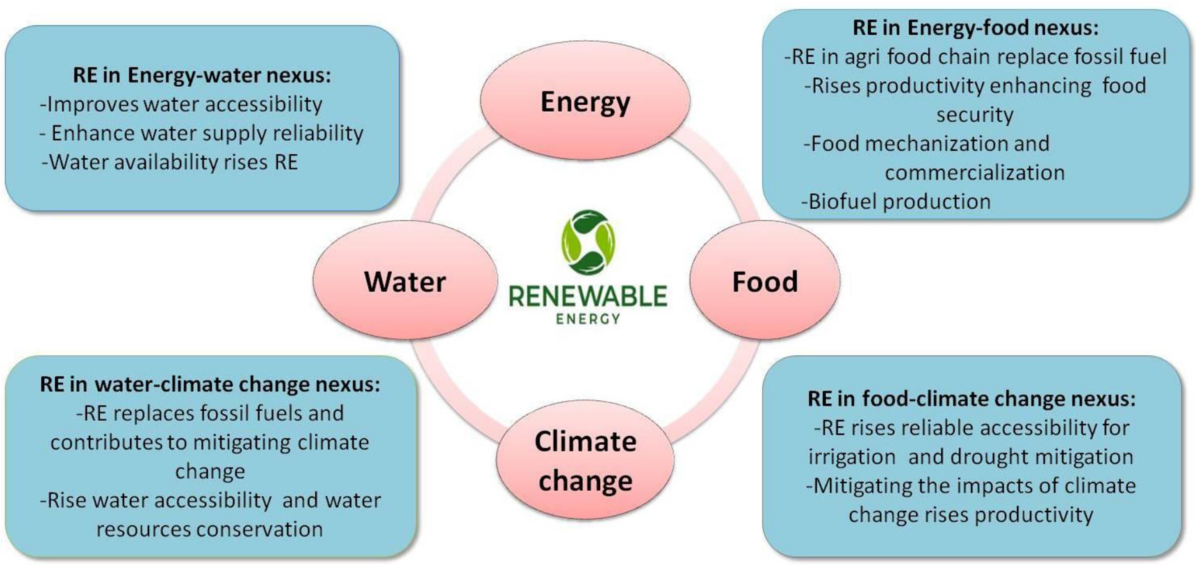

FIGURE 6
Renewable energy opportunities in the water, energy, food nexus, and climate change adaptations.

power plants are constructed close to surface water resources. Flooding as a consequence of climate change and climatic variability has a plethora of negative impacts on agricultural land, and infrastructure including hydro energy production in many cases. For instance, in India, 1,282 people were killed by flooding, with millions of people affected (EM-DAT, 2021). In addition, fuel transport by road faces increased delays due to the interruption in the transportation routes by flooding.

Similarly, with the increase in temperature and drought events, the agricultural sector will require frequent irrigation, and energy demand in the agriculture sector will increase. Bandara and Cai estimated a significant reduction in crop yield in this region due to climate change. This could reduce GDP by 2–5% by 2050 (Bandara and Cai, 2014). The decrease would mainly be due to excessive heat and insufficient water interrupting crop growth in combination with extreme events, especially floods and droughts (Bandara and Cai, 2014). Droughts are severe challenges in South Asia. The major river basins of this region are categorized as having high drought severity (Chapagain, 2017). India and Pakistan reported major droughts at least once every 3 years in the past four decades, while Bangladesh and Nepal also suffer from frequent droughts. It is estimated that 5,308 people were killed; 1.3 billion people were affected. This caused total damage of USD$37.43 billion due to droughts between 1975 and 2015 in South Asia (EM-DAT, 2021).

On the other hand, the overuse of fossil fuel and biomass as a source of energy is contributing to greenhouse gas emissions and global warming. South Asia contributes about 16% of the total global emissions (Tortajada and Saklani, 2018), and 60% of South Asia's emissions come from the agriculture sector. Black carbon mostly comes from the burning of fossil fuel and biomass, and cooking fires. It is considered the main cause of the rapid increase in temperature in the mountains. An estimated, 30% of glacial retreat across HKH was caused by black carbon which might have a significant impact on water availability, energy production, and food production in this region. Due to the over-dependence on natural gas, GHG emissions have increased particularly in more industrialized countries which is further accelerating global warming. CO_2 emissions from the consumption of natural gas in India, the third-biggest greenhouse gas emitter in the world have increased from 7 MMTOE in 1980 to 101 MMTOE in 2015. Energy-related CO_2 emissions in India are almost 5% of total global emissions. Similarly, CO_2 emissions in Pakistan and Bangladesh have increased from 15 to 66 MMTOE and 2 to 52 MMTOE, respectively (EIA, 2018). The emissions are further expected to increase in the future if South Asia does not switch to renewable energy very soon.

The commitment of South Asian nations to achieve SDGs by 2030 have being compromised by the impact of climate change and extremities which is further intensified in the absence of access to reliable sources of energy. For instance, this region depends on groundwater for agricultural use and food security, and fossil fuel is mostly used for groundwater pumping which not only increases the GHG emissions but also increases the variability in production due to timely access to energy for agricultural uses and variability in energy prices. The recent Russia-Ukraine war has increased the prices of energy used in agriculture by 3 to 4 folds resulting in reduced agricultural production and dramatically increase in food prices (Jagtap et al., 2022). Therefore, an increase in the availability of renewable energy in this region will provide an opportunity to achieve SDGs, ensuring a resilient production system and healthy environment for present and future generations.

Renewable energy is central to the water-energy-food nexus and climate change adaptations

Figure 6 depicts the Renewable energy opportunities in the water, energy, food nexus, and climate change adaptations. Renewable energy, mostly hydropower can contribute to achieving energy, water, and food security in various ways and it is also considered the best adaptation option to climate change. The interdependencies among water, energy, and food are multidimensional, and their relationship often has a nexus. Energy is central to the nexus as it is required for food production (especially irrigation) and farm mechanization. Energy is needed for water supply, including the extraction, purification, and distribution of water as well as for adaptation to climate change impacts, such as droughts. But the exploitation of fossil fuel and biomass for energy is creating unsustainability in energy supply, higher energy prices, and, most importantly, GHG emissions and global warming. The energy is needed to be decoupled from fossil fuel to overcome food prices, increase access to food and maintain energy security for other uses.

The use of renewable energy increases agriculture production through farm mechanization and expansion in irrigated land, fertilizer production, food processing, and transportation and helps to switch from traditional subsistence-based agriculture to more competitive and commercial agriculture. Renewable energy could help stabilize food prices for consumers and reduce financial risks for producers and others involved in the food supply chain. Additionally, it could also strengthen the development of non-farm commercial activities, including micro-enterprises, and create opportunities for other livelihood activities (DFID, 2008). Substituting traditional biomass for cooking with renewable energy is imperative for social, health, environmental, and economic development. Additionally, traditional biomass demands more labor and time, particularly affecting women. This effect can be reduced through the introduction of renewable energy in rural areas. Switching from fossil fuel to renewable energy in agriculture is important from the perspective of decreasing the cost of agriculture production, decreasing uncertainties in power supply, reducing fossil-fuel use, and emissions. Therefore, there is a need to integrate energy, water, and food chains with renewable energy, such as hydropower development, that produces little or no greenhouse gases and does not consume water.

Potential of renewable energy development in South Asia

There is huge potential for harnessing hydropower and other renewable energy in South Asia. Harnessing hydropower potential in the region can change the current fossil-fuel-centric energy mixture, ensure a reliable supply of energy, improve energy, water, and food security, and reduce emissions. Some 400 million people in South Asia who lack electricity can get access by tapping the renewable energy potential. In addition, renewable energy helps stabilize volatile energy prices and can play an important role in energy trade and regional power pools. Considering the potential of renewable energy, governments in the region have recently emphasized renewable energy in their national policies.

During COP 21 in Paris on Intended Nationally Determined Contributions (INDCs), India has committed to reducing 33–35% of its greenhouse gas emissions by 2030. This commitment is considered a game changer to change South Asia to a more sustainable mode of energy. Now India is leading the world in terms of solar energy production. There is already some satisfactory growth in other renewable energy in Bangladesh and Pakistan as well.

Similarly, the National Renewable Energy Policy (NREP) of Pakistan has indicated that 2% of the annual development budget will be allocated every year for the development of renewable energy (Solangi et al., 2011). The National Renewable Energy Policy of Bangladesh (2008) has determined that it will make a 10% increase in the share of renewable energy by 2020 of its target (Biswas et al., 2011). Afghanistan has identified in its national plan that electricity exporting is a key strategy for economic development. Nepal and Bhutan policy documents prominently consider hydropower exports as an important source of income for their economies and a major driver of their economic growth. The Energy Policy of Nepal (2006) has envisaged contributing to rural poverty reduction and environmental conservation by ensuring access to clean, reliable, and appropriate energy in rural areas. The Rural Energy Policy of Nepal (2006) of Nepal declared that the government would provide a subsidy amounting to 40% of the total costs of the renewable plants for the private sector/community or households depending upon the type of renewable energy. The government of Nepal has declared that it will generate 20MW of electricity by wind energy in the Three-Year Interim Plan of Nepal (Surendra et al., 2011).

Potentiality of hydropower and other renewables

Hydro power

Hydropower has the most potential but radially exploited clean source of energy in South Asia. Tapping its potential can be the gateway for achieving energy, water, and food security and economic development of the region. The Himalayan topography, good rainfall, and abundance of glacier-fed perennial river basins provide an opportunity for generating an enormous amount of hydropower. The potentiality for the generation of hydroelectricity is higher than other renewables like wind and solar energy considering the economic feasibility, and topographical and meteorological factors on a longer basis.

The total hydropower potential of the six south Asian countries is more than 388 GW. Only 62 GW (16%) is exploited currently. The highest potential exists in India, Pakistan, Nepal, Bhutan, and Afghanistan. Bangladesh holds very little potential. The exploitation rate is very negligible in comparison to the potential. For example, OECD has exploited up to 70% of its hydropower potential and other developing countries have exploited 23% (World Bank, 2009). The hydro potential of South Asian countries is minimally exploited especially in Afghanistan, Nepal, and Bhutan where the exploitation rate is below 6% of the commercially feasible potential supply. The total electricity supply from hydro-source is about 100% in Bhutan, 92% in Nepal, 33% in Pakistan, and 17% in India (see text footnote 2).

At the river basin scale, Brahmaputra holds a total of 200 GW of hydropower potential. This is the greatest in the world but the least exploited (only 10 GW). The Ganga's theoretical hydropower potential is estimated to be about 83,000 MW in Nepal, 21,000 MW in Bhutan, and almost 59,000 MW in northeast India of which half or more is considered to be feasible for harvesting (Rasul, 2015). The Ganges and its tributaries also have huge potential for hydropower development and trade. A recent study conducted by the World Bank suggests that about 25,000 MW of electricity could be generated in the Ganges basin through upstream storage of water in 23 dams and that this could provide benefits worth USD 5 billion per year with little trade-off. The collective potential of hydropower in the Indus River system is about 60 GW, but only 6,720 MW (11%) have been utilized (Rasul, 2015).

Others renewables

Given that South Asia is a tropical region and its weather, both solar and wind could be equally potential sources of renewable energy after hydropower. Currently, the government of India is paying higher attention to solar power and has initiated the Solar Mission as one of the major initiatives for renewable energy. The solar power installed capacity in India has increased from only 3.7 MW in 2005 to about 4,060 MW in 2015, with more than 100% annual growth over the decade. India has a target to generate 100 GW of solar energy by 2022. Similarly, wind energy potential in India accounts for 102 GW; currently, only 21% is installed. India currently stands as the 5th largest wind power producer in the world. India has a target to install 60 GW of wind power by 2022. Pakistan carries a huge potential for both wind and solar energy. Approximately, 6,840–8,280 MJ/m^2 of solar energy can be generated annually and three provinces – namely Balochistan, Sindh, and Punjab have the most potential for solar energy in Pakistan (Solangi et al., 2011). Similarly, Pakistan has 20 GW of economically viable wind power potential (Sheikh, 2009). In Nepal, about 25% of the population is getting access to electricity through renewable sources, such as solar and wind. The annual average solar potential varies from 3.5 to 7.0 kWh/m^2/day and the estimated number of days of sunshine in Nepal is 300 days per year (Mainali and Silveira, 2013). Afghanistan has an annual average solar potential that varies from 4 to 6.5 kWh/m^2/day spread over 300 days of sunshine per year (Mainali and Silveira, 2013). Solar energy is largely untapped in both countries. The current status and potentiality of solar and wind energy in South Asian nations are shown in Table 1.

Opportunities for regional electricity trade

Electricity trade in the South Asian region will increase energy availability, change the current fossil-fuel-dominated energy mixture to clean energy, and, most importantly, the hydro-rich countries will generate substantial revenue through electricity exports. No country in South Asia is energy secure. South Asian countries have different resource endowments, demand trends, and development needs. The feasible hydropower potential of Nepal, Bhutan, and Afghanistan are significantly higher than the domestic demand. India and Pakistan also have higher hydropower potential but their domestic demand is also higher. Bangladesh does not have more hydropower potential and mostly depends on fossil fuels. These complementary opportunities provide an ideal situation for power trade in this region and trade flows from surplus zones to scarce zones. Energy resource surplus countries could benefit from energy exports to the countries with more demand for power. The geographical proximity of hydropower plants from Bhutan and Nepal to the major demand centers in Northern India, and Bangladesh would allow sub-regional interconnections. Theoretically, electricity generated in Nepal could be transmitted to Bangladesh, Bhutan, India, and Pakistan (Pokharel, 2001) through regional electricity trade. Currently, regional energy trade in South Asia constitutes $<5\%$ of total trade within the region. Bhutan is in the process of developing

TABLE 1 Renewable energy and its potential in South Asia (Brown, 2009; Sheikh, 2009; Baruah, 2017; Hydro Status Report, 2017).

Indicators	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan
Theoretical hydropower potential	23,000	–	30,000	184,700	80,000	100,000
Commercially feasible Hydropower potential (MW)	23,000	755	24,000	84,004	43,000	59,000
Hydropower Installed (MW)	442	230	1,615	51,756	867	7,320
Current utilization (%) (of the technical feasible)	1.9	30.4	6.7	61.61	2.01	12.4
Wind potential (MW)	66,000	20,000	760	102,778	448	131,800
Wind Installed (MW)	0.375	1.9	0.6	22,465	–	20,000
Solar Potential (kWh/m^2/day)	6.5	5	4	5	4	5.3
Installed solar photovoltaic (MW)	11	368	–	4,060	–	1,600

export-oriented hydro- projects with success, whereas Nepal has not achieved much success yet. As per the draft NEP (Dec 2016) of India, Nepal would have an export potential of 13.2 GW by 2015 and 24.9 GW by 2035; excluding the 3 major projects of Karnali, Chisapani, and Pancheshwar.

A study done by the World Bank shows this region can save up to US$226 billion during 2015–2040 at the rate of US$9 billion per year by adding only 95 GW energy (only 25% of the total potential) if there is a provision for unrestricted cross-border trade (Timilsina and Toman, 2016). This provision would reduce regional power sector carbon dioxide emissions by 8%, mainly through the substitution of coal-based generation with hydro-based generation. It has been estimated that regional electricity would bring an 8-fold increase in electricity supply and bring electricity access to the entire continent with multiple additional benefits for water management and regional integration.

There are successful electricity trades outside the region which can be a good lesson for South Asia. Examples of successful regional/sub-regional electricity trade include the Gulf Coast Countries (GCC), the Greater Mekong Sub-region (GMS), the Nile Basin Initiative (NBI), Nordpool, the Southern African Power Pool (SAPP), South East Europe (SEE), the European Network of Transmission System Operators for Electricity (ENTSO-E), and Central American Electrical Interconnection System (SIEPAC).

Challenges to renewable energy development in South Asia

Hydropower development in South Asia started long ago. India started hydropower production 150 years ago from Darjeeling, whereas Nepal started it in 1911 with a 500 kW Pharping hydropower plant. Despite the head start, renewable energy development in South Asia did not accelerate regardless of its potential. To date, in South Asia, only 16% of the total hydro potential has been tapped into and hydropower contributes 6% of the total energy mix (see text footnote 2).

This section describes the major limitation to the development of hydro and other renewable energy in South Asia.

Policy barriers

Despite the fact that renewable energy is critical for development, the renewable energy sector has not received significant attention in the policy arena. Governments in most South Asian countries are directly and indirectly providing subsidies to import fossil fuels and that has favored the increased use of imported fossil fuels.

In Bangladesh, fossil fuel subsidies have exceeded 3% of the GDP for many years (see text footnote 2). The significant increase in the use of fossil fuels in India is influenced by the subsidy for fossil fuels. High levels of regulation and trade barriers in electricity trade and low incentives for private sector participation are the other policy challenges inhibiting hydropower growth in South Asia. Water policies and institutions in the transboundary basin scales and regional scales in South Asia are fragmented and have led to poor coordination for hydropower development, water resources planning, and management. Moreover, the generated hydroelectricity in South Asia has faced challenges in cross-border trade with its limited transmission lines (Timilsina and Toman, 2016). For instance, policy barriers have been one of the major challenges in the trade of hydroelectricity between Nepal and India which imposes conflict on bilateral and multilateral agreements. The strategic multilateral agreements between the South Asian countries are equally important rather than the bilateral agreements of most of the nations with India. Thus, it requires the periodic amendment of policies and laws favoring the cross-border hydroelectricity trade including the establishment of the regional/sub-regional grids and institutional arrangements in the region.

Limited infrastructures

Hydro-power sector infrastructure includes hydro dams and transmission at the national, sub-regional, and regional levels. The infrastructure development in this region is severely challenged particularly in mountainous countries like Nepal, Bhutan, Afghanistan, and the northern part of India. Infrastructure development in this region is severely challenged by rugged terrain, and higher risks of natural disasters, such as Glacial Lake Outburst Floods (GLOFs) and sedimentation. These countries have limited technical capabilities for infrastructure development.

The biggest challenge of renewable energy is that it involves high initial capital costs and a long payback period. The cost of dam construction is very high in mountainous countries like Nepal. For example, Exim Company of China constructed the West Seti Dam in Nepal with 750 MW capacity for 1.6 billion USD. Similarly, a hydro project of 2,600 MW was constructed in Nigeria by the same company for USD 1 billion during the same period (McDonald et al., 2009). The resource required for hydropower infrastructure development in South Asia is very high. In India alone, the Planning Commission estimates that $500 billion is required for the next 5 years to meet the energy needs of a growing population and rapid urbanization through renewable energy (World Bank, 2009).

The South Asian nation has barely developed basic infrastructures like transportation in the hilly areas. Most of the potential hydrogenation sites are located in remote areas and, therefore, the lack of basic infrastructure development increases the cost of the entire project. Furthermore, the lack of basic infrastructures such as transmission lines and regional power grids has been a major challenge for the cross-border electricity trade. Direct foreign investment or national investment in the development and expansion of such infrastructures would help in cross-border trade in South Asia.

Suggested solutions for promoting hydropower and other renewables in South Asia

The promotion of broader regional and sub-regional cooperation goes beyond the current bilateral arrangement. A nexus approach for policy coherence and institutional harmonization, collaborative investment in infrastructure, and private sector participation are the key areas for promoting renewable energy and hydropower in South Asia. Research and information sharing are equally important to examine the interventions in the South Asian context.

Regional cooperation should go beyond the current bilateral arrangement of energy trade

Energy can be the entry point for regional and sub-regional cooperation in South Asia. A strong bilateral trade is the entry point for establishing a regional power pool and regional electricity trade (Singh et al., 2015). Such regional and sub-regional cooperation help to increase mutual benefit through stimulating emerging opportunities in renewable energy, particularly in the hydropower sector to achieve water, energy, and food security, and climate change adaptation at transboundary and regional scales. The bilateral and sub-regional arrangements that exist today are sector-specific and cannot fully utilize those opportunities. The lack of timely cooperation in this region may result in many non-cooperative and unilateral efforts and can result in negative externalities to the neighboring countries and future potential conflicts on water. For example, unilateral hydropower development and water diversion plans in the Ganges and Brahmaputra Rivers basins by India may bring environmental disasters and conflicts in the decades to come with Bangladesh being affected the most negatively (Rahaman, 2012). The South Asia region is losing USD$10 billion dollars annually due to the lack of proper water resource development (see text footnote 2) and hydropower development. So, for mutual benefit and co-development, broader regional cooperation is important in this region, keeping the energy at the center.

Nexus approach for integrated planning, policy coherence, and institutional harmonization

The nexus approach helps to address energy, water, and food security and climate change adaptation at regional scales for which integrated planning, policy coherence, and institutional harmonization play a crucial role. Realizing the energy challenges of South Asia, each south Asian country has developed its own plan to meet the energy demand. Undermining the cross-sectorial and cross-country impacts, such divergent, fragmented, and independent sectoral approaches are more risky, expensive, and unsustainable, and can also create serious problems at national and transboundary scales. Therefore, the planning and implementation of hydropower should be integrated with nexus components, such as water and food security and climate change.

The nexus approach helps to increase the benefit by reducing transaction costs, generating additional synergies, and reducing the trade-off at different scales. The nexus approach treats the issues holistically and establishes linkages across boundaries. It cannot be applied to the status-quo policy and institutional landscape. Policy coherence and institutional harmonization are key factors for operationalizing the nexus approach at different scales to achieve energy, water, and food security in South Asia. For policy coherence and institutional harmonization, the public sector can play a vital role in coordinating, setting incentives, and being the regulatory mechanism to make policy more coherent across institutions and sectors. There might be conflicting policies like subsidies for energy use in agriculture that deplete the groundwater. For harmonizing policies and institutions, there is a need to revise policies that are developed focusing on a single sector. These policies should be upgraded or removed if they are found to be counterproductive to water, energy, and food security.

There is a two-way relationship between climate change and three nexus components. The nexus should therefore be linked with issues of climate and its variability. Accordingly, the energy, water, and food policies have to be aligned to build climate resiliency. It is a time to move from sectorial to cross-sectoral adaptation and from local to the regional level to find a sustainable and holistic solution. Therefore, it calls for a strong intervention in the hydro-power sector to positively enhance the food-water-energy nexus. There is now a growing realization of the need to address energy security from a regional perspective. The role of regional and sub-regional institutions such as the South Asian Association for Regional Cooperation (SAARC), Bangladesh, Bhutan, India, Nepal (BBIN), and South Asia Regional Initiative/Energy's (SARI/E) are increasingly important and needs strengthening to bring policy coherence at sub-regional and regional level in South Asia.

Collaborative investment on multi-purpose projects and the role of private sectors

Collaborative investments in hydro-infrastructure and encouraging private sector participation in infrastructure development can aid the infrastructure challenges in this region. There is a need for substantial improvements in water infrastructure to meet food, water, and energy security. The cost of water infrastructure is excessively high with high risks and uncertainties and a long payback period. Water infrastructure also requires a high level of technology. It is very hard to channel large investments, especially for the hydro-rich upstream countries, such as Bhutan, Nepal, and Afghanistan. There is a need for collaborative investment in multi-purpose hydro projects to exploit the hydro potential of this region. India and Pakistan are relatively strong in technology for infrastructure development and this strength can be exploited through regional cooperation for infrastructure development in this region. Multi-objective collaborative water infrastructures are the implication of the nexus approach on the ground and a cost-minimizing approach. Multilateral organizations such as the World Bank have been actively engaged to foster regional cooperation for infrastructure development in this region (Bandyopadhyay, 1995). Collaboration on water infrastructures fosters regional trade and economic integration where water infrastructure acts as the entry point for the sub-regional and regional cooperation in this region (Whittington, 2004).

Normally, the private sectors are generally unwilling to invest in water infrastructure development in South Asia because of the large investment, long payback periods, risks, and government policies. For example, the private sector investment in hydro-power infrastructures in Nepal is around 20% (Shah and Kishore, 2012). Power companies are licensed only to develop power projects (Baruah, 2017) and irrigation projects from the same water source go to two different companies.

There are good examples that the Chinese Export–Import Bank and state-owned enterprises, and private firms are now involved in at least 93 major hydro projects in the world (McDonald et al., 2009). There are several potential private sectors at the regional and global scales. The private sector increases resource efficiencies through the sustainable use of resources. National and regional governments bring conducive policies and regulations to bring the private sector to the main frontier of hydropower development and other renewable energy.

Research

Empirical evidence shows that 1 dollar on expenditure in research in the water sector brings benefits of more than 100 dollars (Kattelmann, 1987) as it helps to minimize the risks of project failure and helps to create a conducive environment for the implementation. The research helps to generate more comprehensive nexus knowledge. Better knowledge improves the understanding of risks and provides a more solid basis for nexus decisions. The optimum utilization of water resources for energy, water, food security, and climate change adaptations in South Asia requires more detailed research at the transboundary and regional levels to understand the risks and develop reliable scenarios. Another goal of the research is to elaborate consistent scenarios of possible socioeconomic development and climate change impacts with the purpose of identifying future development opportunities as well as understanding the implications of different nexus-focused policies in the South Asian context. There are several threats imposed on the hydro sector from climate change, natural hazards, seismicity, and socio-economic and political drivers. There is a need for rigorous study before the implementation of such a big project.

The bio-physical challenges of integrated water resource development in this region are sedimentation control, natural hazards, and climate change. The melting of glaciers in the Himalayas because of climate change has resulted in the formation of large and rapidly swelling glacial lakes. Estimates suggest that ∼2,300 glaciers in Nepal's Himalayan region contain growing glacial lakes which are potentially dangerous to the water infrastructure. These lakes can damage agricultural fields, lives and livelihoods, and critical infrastructure, including hydropower. Glacial lake outburst is a potential threat to integrated water infrastructures, including hydropower.

Another research gap is in sedimentation. The Ganga is one of the most sediment-laden rivers in the world. The Ganges and the Brahmaputra carry over a billion tons of silt to the Ganges–Brahmaputra–Meghna (GBM) delta every year (Jeuland et al., 2013). The sedimentation issue is largely underestimated and less studied in this region (Kattelmann, 1987). Socio-economic and bio-physical factors should be clearly understood before the implementation of big hydro projects in South Asia and ICIMOD being a research organization can support the generated knowledge which will be helpful for hydropower development to achieve energy, water, and food security in South Asia.

Conclusion

The lack of utilization of the full potential of renewable energy by the nations in this region has highly compromised the food, water, and energy security of the people. Moreover, the impact of climate change is expected to further exacerbate the food, water, and energy insecurity in this region. This article identifies the roles of renewable energy sources in achieving energy, water, and food security for nations in the South Asian region and provides suggestions for further development in the utilization of renewable resources. The potential for the development of hydropower and other renewable energy and opportunities for multilateral energy trade to increase the availability of energy are identified along with potential challenges. This article suggests possible solutions for the promotion of hydropower and other renewables in South Asia through different approaches. The nexus approach for integrated planning, policy coherence, and institutional harmonization is one of the approaches that this article focuses on. This helps to increase the benefit by reducing transaction costs, generating additional synergies, and reducing the trade-off at different scales. These approaches will help mitigate several challenges faced in the process of improving energy, food, and water security. A secured supply of food, water, and energy improves the quality of life in the region and improves economic and infrastructural development processes in the region. The use of renewable energy at its full potential is considered one of the effective adaptation measures to climate change and attaining SDGs in South Asia.

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

NN prepared concept note, methodology, analysis, and writing. PC prepared concept notes, writeup and editing. YR collected primary and secondary data, analysis, interpretation, and write-up. BG worked in data collection, analysis, visualization, and write up. RB worked in data visualization, write-up, editing, and proofreading. All authors contributed to the article and approved the submitted version.

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.

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Detection of cassava brown streak ipomoviruses in aphids collected from cassava plants

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Cassava is an important staple food in Africa and a major source of carbohydrates for 800 million people globally. However, cassava suffers severe yield losses caused by many factors including pests and diseases. A devastating disease of cassava is cassava brown streak disease (CBSD) caused by the cassava brown streak ipomoviruses (CBSIs) (family *Potyviridae*), *Cassava brown streak virus* (CBSV), and *Ugandan cassava brown streak virus* (UCBSV). Spread of CBSD is mainly through planting infected stem cuttings used for propagation. Transmission of CBSIs by the insect vector *(Bemisia tabaci)* has been reported. However, experimental transmission efficiencies of CBSIs are usually low. Recent research has showed the occurrence of a DAG motif associated with aphid transmission in other potyviruses, within the coat protein gene of CBSV. Consequently this study aimed to explore the possibility that besides whiteflies, aphids may transmit CBSIs. Cassava plants were assessed during a survey for occurrence of CBSD and aphids as potential alternative CBSIs vectors. We collected aphids from CBSD-symptomatic and symptomless cassava plants within farmers' fields in Uganda during April–July 2020. The aphids were analyzed for the presence of CBSIs by reverse transcriptase-polymerase chain reaction (RT-PCR) and to determine aphid species using mitochondrial cytochrome oxidase (mtCOI) barcoding. Unusual aphid infestation of cassava plants was observed at 35 locations in nine districts across Uganda and on 11 other plant species within or adjacent to cassava fields. This is the first report of aphids infesting cassava in Uganda. Molecular analysis of the aphid confirmed presence of three different aphid species in the surveyed cassava fields, namely, *Aphis solanella*, *Aphis fabae mordvilkoi*, and *Rhopalosiphum sp*. mtCOI nucleotide sequences for the aphids in which CBSIs were detected are deposited with Genbank under accession numbers OP223337-40. Both UCBSV and CBSV were detected by RT-PCR in aphids collected from cassava fields with CBSD-affected plants. The CBSIs were detected in 14 aphid samples collected from 19 CBSD-symptomatic cassava plants. These results suggest the ability of aphids to acquire CBSIs, but transmission experiments are required on their vector potential.

KEYWORDS

cassava, disease, aphids, cassava brown streak ipomoviruses, cassava brown streak disease, food security

1. Introduction

Cassava (*Maninot esculenta* Crantz, family *Euphorbiaceae*) is a major staple food and income generation crop for farmers across sub-Saharan Africa. In addition, cassava is a hardy crop that is resilient to drought and performs well on marginal soils where other crops would fail. Cassava has also been prioritized in many African countries as a commodity that can drive industrialization through its use as a raw material in the production of livestock feed, starch, alcohol, pharmaceuticals, biofuels, and bio-polymers. However, the crop is affected by a number of biotic stresses including devastation by pests and diseases. The most significant yield losses are caused by two major viral diseases, namely, cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), reported to cause an estimated annual loss of about US$1 billion (Hillocks et al., 2001; Mohammed et al., 2012). A pandemic of CBSD is currently spreading in eastern, central, and southern Africa, threatening cassava production and the livelihoods of communities that primarily depend on the crop (Alicai et al., 2007; Legg et al., 2011). CBSD-induced necrosis reduces the quantity and quality of storage roots, causing yield losses of up to 70% (Hillocks et al., 2001). A study in Kenya, Tanzania, Malawi, and Uganda estimated losses due to CBSD to be US$750 million annually (Maruthi et al., 2005).

Cassava brown streak disease is caused by two positive-sense single-stranded RNA (+ssRNA) viral species, *Cassava brown streak virus* (CBSV) and *Ugandan cassava brown streak virus* (UCBSV), collectively referred to as CBSIs belonging to the genus *Ipomovirus* in the family *Potyviridae* (Mbanzibwa et al., 2009a; Tomlinson et al., 2018). The genome of the CBSIs is about 8.9–10.8 kb, which is translated into a polypeptide of 10 proteins (5′-3′), namely, P1, P3, 6KD1, cylindrical inclusion (CI), 6KD2, VPg, nuclear inclusion protein a (NIa), nuclear inclusion protein b (NIb), HAM1h, and coat protein (CP) (Monger et al., 2001; Mbanzibwa et al., 2009b; Winter et al., 2010; Tomlinson et al., 2019). All the proteins serve different roles in different stages in the viral infection cycle, including viral replication, translation, cell-to-cell movement within the host, and transmission between vectors and the host (Llave et al., 2002).

Often, CBSD is unrecognized in the field because of its inconspicuous foliar symptoms compared to those for CMD and cassava green mite (CGM). Symptoms of CBSD on the leaf can take different forms depending on the cassava variety, the age of the plant, and the conditions under which it is growing (Hillocks and Jennings, 2003). The disease gets its name from "brown streak", a term which refers to the brown lesions often observed on the stem of CBSD-affected plants. Symptoms can appear on either leaves, stems, fruits, storage roots or are exhibited on more than one organ. The necrosis on the storage roots is a symptom of great economic importance (Hillocks et al., 1996).

Currently, CBSIs vector specificity is unclear. This is mainly because most of the vector transmission studies have shown very low transmission efficiencies. For instance, transmission with the whitefly vector (*B. tabaci*) was only 22% (Maruthi et al., 2005). The CBSIs have been shown to be transmitted by cassava whitefly (*B. tabaci*) in a semi-persistent manner. However, the observed low transmission efficiencies of CBSIs by whiteflies do not match the rapid CBSD spread observed in the fields, especially under epidemic conditions (Maruthi et al., 2005). This observation suggests possibly another vector involved in CBSI's transmission other than whiteflies, and this needs further investigation. Determining if there are other vectors for CBSIs is important in integrated pest management (IPM) programs required to control the spread of the disease (Dombrovsky et al., 2014).

Interestingly, unusual occurrence of a DAG motif within the coat protein gene of CBSVand implications for its vector transmission was recently reported (Ateka et al., 2017). The highly conserved DAG motif is associated with aphid transmission of potyviruses. Presence of the motif in the CBSV genome denotes aphid transmission possibility. Initially, aphid transmission was not considered possible for CBSIs, as they do not encode HC-Pro proteins, which in other *Potyviridae* are involved in aphid transmission. The HC-Pro acts as a "bridge" between the aphid stylet and the virus particle. The HC-Pro has an affinity for both the viral coat protein (CP) DAG motif (through its PTK motif) and the receptors in the aphid (through its KITC motif) (Whitfield et al., 2015). This interaction thus acts as a bridge to allow the retention of the virus particles in the aphid stylet. Hence, the presence of the highly conserved DAG and PTK motif in the CBSV CP and the KITC in the CBSV P1 sequences have been highlighted, which raises the possibility for CBSV to be transmitted by aphids in addition to whiteflies (López-Moya et al., 1999).

Arising from these previous findings, it was important to undertake studies that characterize and specify the vector(s) responsible for transmission of CBSIs.

2. Materials and methods

2.1. Collection of aphids from plant species other than cassava

Aphids were initially collected from fields at and near the National Crops Resources Research Institute (NaCRRI), Namulonge, during the months of May to December 2019. For this location, there were few aphids on cassava plants compared to other plant species growing within or near cassava fields.

2.2. Survey and collection of aphid samples from farmers' cassava fields

2.2.1. Field surveys

Ten different districts in Uganda were surveyed during the months of April to July 2020, and aphids collected from cassava fields. During the survey, considerations were made to collect aphids from fields having CBSD and those without any CBSD symptoms. For the fields with CBSD, the incidence of the disease was recorded.

2.2.2. Selection criteria for survey districts

The collection of aphids considered districts that have been reported to have high incidences of cassava brown streak disease (CBSD) and were considered to be representative of CBSD disease situation in Uganda. Some districts, like Bukwo, had previously been reported to have high incidences of aphids in cassava fields and were thus included in this survey.

Thus, in this survey, 10 districts in Uganda were selected. Of these, eight districts were in the Eastern parts of Uganda, including Kamuli, Iganga, Budaka, Bukedea, Bulambuli, Kapchorwa, Kween, and Bukwo. Two districts, were in the Central parts of Uganda including Luwero and Wakiso districts.

2.2.3. Data collection and field background information

Data was recorded in the field using Excel-field datasheets which captured information about the date and time. Details of location were recorded and this included the district, sub-county, village, and farmers' names. Geographical referencing (longitude, latitude, and altitude) of each field was obtained using the global positioning system (GPS) software. Information was recorded on cassava varieties grown, number of cassava fields nearby, field size, age of cassava plants and intercrops.

2.2.4. Sampling domain, field selection and sampling approach

Surveys were conducted in targeted districts mentioned above, and the sampling domain was a district. In each district, fields were randomly sampled. Fields were sampled along major and accessible roads within the districts. Fields were selected at regular intervals of 7 km between sites or thereafter when a suitable cassava field is found. The age of cassava plants sampled was between 3–10 months old cassava fields, and this information was provided by the farmer. At each site (cassava field), 30 plants were assessed at regular intervals across the two diagonals, and data were collected from any cassava variety that occur along the diagonals. Information on the cassava varieties that occur in the sampled field was also recorded.

2.2.5. Parameters measured in the field

Parameters measured in the survey included CBSD severity and incidence and number of aphids on a plant. To determine whether they contain and can possibly transmit CBSIs, aphids isolates were collected and characterized.

2.2.6. Cassava brown streak disease severity assessment

CBSD severity was assessed on the stems and leaves of cassava plants. This was assessed for each of the 30 plants using a scale of 1–5, where 1 represents no symptoms and 5 the most severe symptoms that include stem streaking and shoot tip die-back (see scale below) (Ogwok et al., 2010; Ano et al., 2021).

Scale: Symptom description

1. No apparent symptoms of CBSD
2. Mild vein yellowing/chlorotic blotches on some leaves, but no stem lesions
3. Pronounced vein yellowing/chlorotic blotches on most leaves and mild stem lesions
4. Pronounced vein yellowing/chlorotic blotches on most leaves, moderate lesions or streaks on stems, or wilting but no die-back
5. Pronounced vein yellowing/chlorotic blotches on leaves, severe lesions or streaks on stems, defoliation, and die-back.

2.2.7. Collection of aphids for molecular characterization

Adult aphids found on cassava plants were collected using an aspirator from the fields in which they occured. The aphid samples from such fields were separately put in a 1.5-ml sample tube containing 80% ethanol and stored at room temperature until nucleic acid extraction.

2.2.8. Collection of cassava leaf samples to analyze for the presence of CBSIs

For each plant from which aphids were collected, a corresponding cassava leaf was picked, rolled carefully, and put into a 2.0-ml microfuge tube containing 1.0 ml of RNA-later or CTAB solution for preservation. The tubes were labeled appropriately and sealed. The samples were kept at room temperature until RNA extraction.

2.3. Molecular analysis for CBSIs detection and mtCOI barcoding

2.3.1. RNA extraction from cassava leaves

CTAB was used to extract nucleic acids from cassava leaves (Abarshi et al., 2010). 100 mg of leaf tissue was ground in 1,000 μl of extraction buffer 2% CTAB (cetyltrimethyl ammonium bromide) containing 100 mM Tris–HCl, 20 mM EDTA, 1.4 M NaCl, and 0.2% β-mercaptoethanol (v/v) in a sterile motor and pestle. 600 μl of sap was poured into a sterile tube and vortexed briefly and then incubated in a water bath at 65°C for 10 min. 600 μl of chloroform:isoamyl alcohol (24:1) was added and the emulsion was mixed by inverting the tube. The mixture was centrifuged at maximum speed for 10 min at room temperature. About 450 μl of aqueous layer was removed, and the nucleic acid precipitated with 450 μl ice-cold isopropanol (20°C). The mixture was incubated at −20°C for 30 min. After the incubation, the mixture was centrifuged for 10 min at 6500 rpm to pellet the nucleic acids. The pellet was washed with 70% ethanol before air drying. The nucleic acids pellets were dissolved in 50 μl sterile distilled water. The isolated total nucleic acids samples were then stored at −80°C until they are ready to be used. The concentrations of the extracted nucleic acid were measured using a Nanodrop, and 50 ng of genomic RNA was used for cDNA synthesis using the Revert Aid First Strand cDNA Synthesis Kit (Thermo Scientific™).

2.3.2. Nucleic acid extraction from aphids

The chelex extraction method was used to extract nucleic acid from single aphids (Asghar et al., 2015). The aphids were initially soaked on a paper towel to remove any residual ethanol before using them in the extraction. The aphids were then crushed with the Chelex resin (100 μl resin +10 μl of Proteinase K) in a 1.5-ml Eppendorf tube using a micropestle. The mixture was incubated at 56°C for 20 min, and the Proteinase K heat inactivated by incubating the mixture at 94°C for 5 min. Centrifugation was done at 13,000 rpm for 5 min and 100 μl of the supernatant containing the extracted nucleic acid was taken and stored in an Eppendorf tube. The concentrations of the extracted nucleic acid were measured on a Nanodrop, and the nucleic acid was used for cDNA synthesis with the RevertAid First Strand cDNA Synthesis Kit (Thermo Scientific™).

2.3.3. First-strand cDNA synthesis

First-strand cDNA was synthesized using the RevertAid First Strand cDNA Synthesis Kit (Thermo Scientific™) according to the manufacturer's instructions, and oligo $(dT)_{18}$ was used as the initial primer to synthesize the first strand of cDNA. The synthesized cDNA was then used as a template in a PCR reaction. The reaction set up for cDNA synthesis was as follows. Template RNA (Total RNA) 0.1–5 µg, oligo $(dT)_{18}$ Primer (10 µM) 1 µl, Nuclease Free Water 11 µl. The samples were then incubated at 65°C for 5 min, centrifuged, and then chilled on ice. To the reaction above, the following were added in order: 5× Reaction Buffer, 4 µl, RiboLock RNase inhibitor 1 µl (20 U/µl), 10 mM dNTP Mix 2 µl; RevertAid RT 2 µl (20 U/µl), Nuclease Free Water 20 µl total volume. The reaction was incubated at 42°C for 60 min and then terminated by incubation at 70°C for 5 min.

2.3.4. Reverse transcriptase-PCR

The synthesized cDNA was used in RT-PCR reactions which was performed in a 20 µl of final reaction volume that contained 7 µl of sterile distilled water, 10 µl of 2× PCR ready mix containing Taq DNA polymerase (Thermo Scientific™), and 1 µl each of the forward (10 µM) and reverse (10 µM) primers. The appropriate positive and negative controls were included for each of the PCR.

For the detection of CBSIs in the cassava leaves and aphids, a universal diagnostic primer pair CBSDDF2 (5′-GCTMGAAATGCYGGRTAYACAA-3′) and CBSDDR (5′-GGATATGGAGAAAGRKCTCC-3′) for detection of both CBSV and UCBSV in one reaction was used with an expected product size of 344 bp and 438–440 bp, respectively (Mbanzibwa et al., 2011).

For mtCOI barcoding of the aphids, primers HCO2198-puc (5′-TAAACTTCWGGRTGWCCAAARAATC-3′) and HCO-2198 (5′-TAAACTTCAGGGTGACCAAAAAATCA-3′) amplifying the 5′-terminal of the mitochondrial cytochrome C oxidase subunit 1 gene (COI) in insects (Folmer et al., 1994) were used.

PCR was carried out in a PTC-200 Engine thermocycler (Bio-Rad) with the program as an initial denaturation at 95°C for 2 min, followed by 36 cycles of denaturation at 95°C for 30 s, annealing for 30 s (temperature varying with primers) and extension at 72°C for 1 min per kb (depending on the length of the expected PCR product) and a final extension at 72°C for 10 min. PCR products were analyzed by gel electrophoresis in a 1X TAE buffer on a 1.0% agarose gel, stained with ethidium bromide, visualized under UV light, and documented the gel picture.

2.3.5. Sanger sequencing of PCR amplicons from aphid samples

To determine the aphid species infesting cassava in Uganda, Sanger sequencing was performed on the PCR products from aphids that had been confirmed to contain U/CBSV. The PCR amplicons were sent to the Netherlands. Sequencing was carried out at Macrogen Inc. (Macrogen Europe Laboratory, Amsterdam, The Netherlands). The sequencing results were analyzed by BLAST analysis using the NCBI BLASTn tool.

3. Results

3.1. Occurrence of aphids on weed plants within and adjacent to cassava fields

In a preliminary assessment, aphids were found on cassava, and 11 other plant species near and in cassava fields around Namulonge in central Uganda. Individual aphids collected from the different plant species were analyzed by molecular characterization. It was observed that there were more aphids on weed plants adjacent to cassava fields than on cassava plants at Namulonge. The identities of these plants are indicated in Supplementary Table 1. The aphids present on weed plants are shown in Figure 1.

3.2. Aphids infesting cassava plants in farmers' fields

Of the 10 districts surveyed, up to seven cassava fields were assessed per district, and samples were collected (Supplementary Table 2; Figure 2). In Kween district, there were no cassava fields found as the main crops grown were bananas and maize. Aphids were found on cassava plants at 35 locations in nine districts of Uganda (Supplementary Table 2; Figures 2, 3). For the four districts of Kamuli, Iganga, Budaka, and Bukedea, aphid populations on cassava were low (Figure 2). Districts with the highest prevalence of aphids were Bukwo (aphids found in 80% of visited fields) and Bulambuli (all, 100% of visited cassava fields). Cassava fields surveyed in Bulambuli district had CBSD on most of the sampled cassava plants. Therefore aphids collected from the fields in the Bulambuli district were selected for molecular analysis for the detection of CBSIs. In contrast, no CBSD was observed within the cassava fields in Bukwo, though high aphid populations were recorded. In Luwero district, a field in which CBSD was observed had a few aphids collected from the CBSD symptomatic cassava plants. Most cassava varieties from which aphid samples were collected are known to be CBSD susceptible. In total, 196 aphid samples were collected from farmers' cassava fields, and the same number of cassava leaf samples were collected (Supplementary Table 2). This study provides the first clear record on occurrence of aphids on cassava in Uganda and requires further understanding. Unusual occurrence of heavy aphid infestation on cassava was previously observed in eastern Uganda in Bukwo and Sironko districts, but remained undocumented. Leaves of affected cassava plants appeared distorted and curled inward displaying a typical symptom of feeding damage by aphids. Although such symptoms were not observed during the present survey, aphid populations remained higher in that region compared to others.

3.3. mtCOI barcording of aphids from non-cassava plant species

Thirty individual aphid samples from different host plant species collected within or near cassava fields at Namulonge and Bulambuli were analyzed by PCR for the mtCOI gene and a 700-bp fragment was amplified (Figure 4). The aphid samples were collected from different plant species, as indicated in Supplementary Table 1. The final results of the mtCOI barcoding allowed definitive identification of aphid species prevalent on cassava that can be used in follow-up studies.

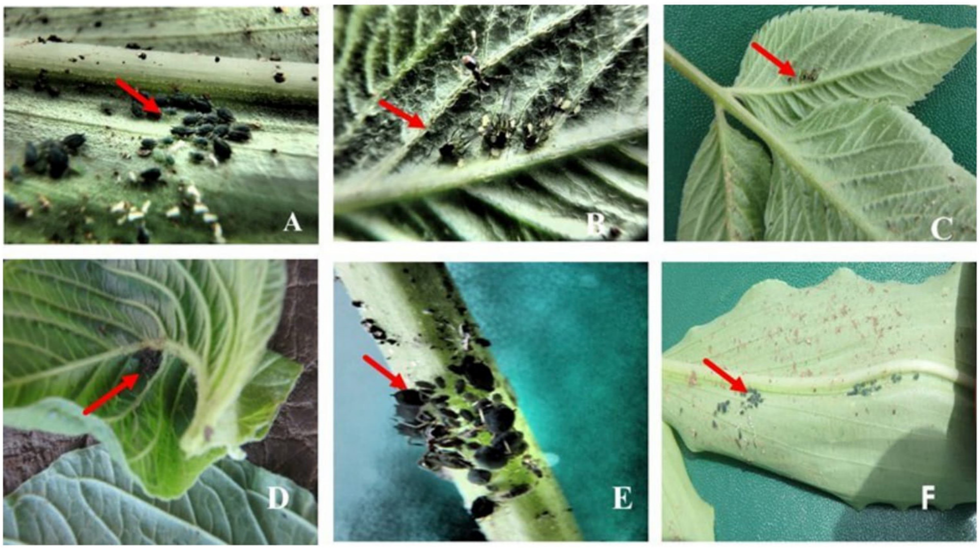

FIGURE 1
Aphids found on other plant species growing within or near cassava fields. **(A)** *Commelina africana* (Nanda—local name) with black wingless aphids. **(B)** *Bidens Pilosa* (blackjack) with black winged aphids. **(C)** Blackjack with black winged aphids. **(D)** *Aspilia Africana* (Makayi—local name) with black wingless aphids. **(E)** Blackjack stem with black wingless aphids. **(F)** *Commelina africana* with nymphs.

3.4. CBSIs confirmed in CBSD symptomatic plants within cassava fields from which aphids were collected

Overall, 196 cassava leaf samples were collected corresponding to each plant from which aphids were collected from farmers' fields. Of these, leaf samples from representative plants showing clear CBSD symptoms were selected to confirm the presence of CBSIs in the cassava fields from which aphids were collected. Priority was given to four samples from fields in Luwero (1), Wakiso (1), and Bulambuli (2) districts because these had plants with CBSD symptoms and high aphid populations. RT-PCR products of 340 bp (CBSV) and 440 bp (UCBSV) were obtained (Figure 5). The sample from Luwero had mixed infection (both CBSV and UCBSV), while that from Wakiso tested positive for CBSV and samples from Bulambuli contained UCBSV.

3.5. CBSIs detected in aphids from cassava fields with CBSD affected plants

A sub-sample of 20 aphids was selected from two fields in the Bulambuli district for detection of CBSIs in the aphids. These samples were analyzed by RT-PCR following a protocol for simultaneous detection of CBSV and UCBSV. 14 out of 19 (73.7%) aphid samples were collected from CBSD symptomatic cassava plants tested positive for CBSIs (Figure 6; Supplementary Table 3). One aphid sample taken from a healthy cassava plant tested negative by RT-PCR. All the aphids (14) that tested positive had CBSV, and 8 of those also had UCBSV in addition [double bands for the 440 bp (UCBSV) and 340 bp (CBSV)]. It was also noted that the intensity of the bands was low in the aphids (Figure 6) as compared to the cassava plants (Figure 5), which may be indicative of low virus titers of CBSIs in the aphids. To further confirm species identities of the aphids in which the CBSIs were detected, the same aphid samples were characterized by mtCOI barcoding and respective PCR products sent for Sanger sequencing. The sequence results were analyzed by Blastn in the NCBI database. This confirmed three aphid species as those infecting the cassava namely, *Aphis solanella*, *Aphis fabae mordvilkoi*, and *Rhopalosiphum sp*. Overall *Aphis solanella* was the most prevalent species for the analyzed samples (Supplementary Table 3). Nucleotide sequences for the aphids were deposited in the GenBank database under accession numbers OP223337, OP223338, OP223339, and OP223340.

4. Discussion

Aphids are important insect pests of plants and vectors for plant-infecting viruses (Ng and Perry, 2004; Gadhave et al., 2020). To successfully transit a virus, there are a number of different viral-vector interactions that come into play with viruses encoding proteins that play a role in virus transmission. The viral HC-Pro and CP have been reported to be the main proteins involved in aphid transmission (López-Moya et al., 1999; Ala-Poikela et al., 2011; Ateka et al., 2017).

The major reported cassava virus diseases in Africa are cassava mosaic disease (CMD) caused by cassava mosaic begomoviruses (Family *Geminiviridae* and genus: *Begomovirus*) and CBSD with whiteflies (*B. tabaci*) as vector for both (Thresh et al., 1994; Hillocks and Thresh, 2000). However, low transmission efficiency of CBSIs by whiteflies has continued to generate interest in the possibility of other unexplored vectors (Maruthi et al., 2005).

In this study, it was observed that aphids were found in cassava fields infected with CBSIs and on other plant species near or around cassava fields in Uganda. This observation may indicate that, besides spread by planting infected plant materials and whiteflies, aphids may possibly be other unexplored vectors responsible for CBSD spread (Ateka et al., 2017). This observation confirms that aphids can acquire and retain the CBSIs; however, transmission studies are required to confirm if the aphids can transmit the CBSIs (Ng and Perry, 2004; Gadhave et al., 2020). This study follows the notion from an earlier report that a DAG motif present in the CP of CBSV is indicative

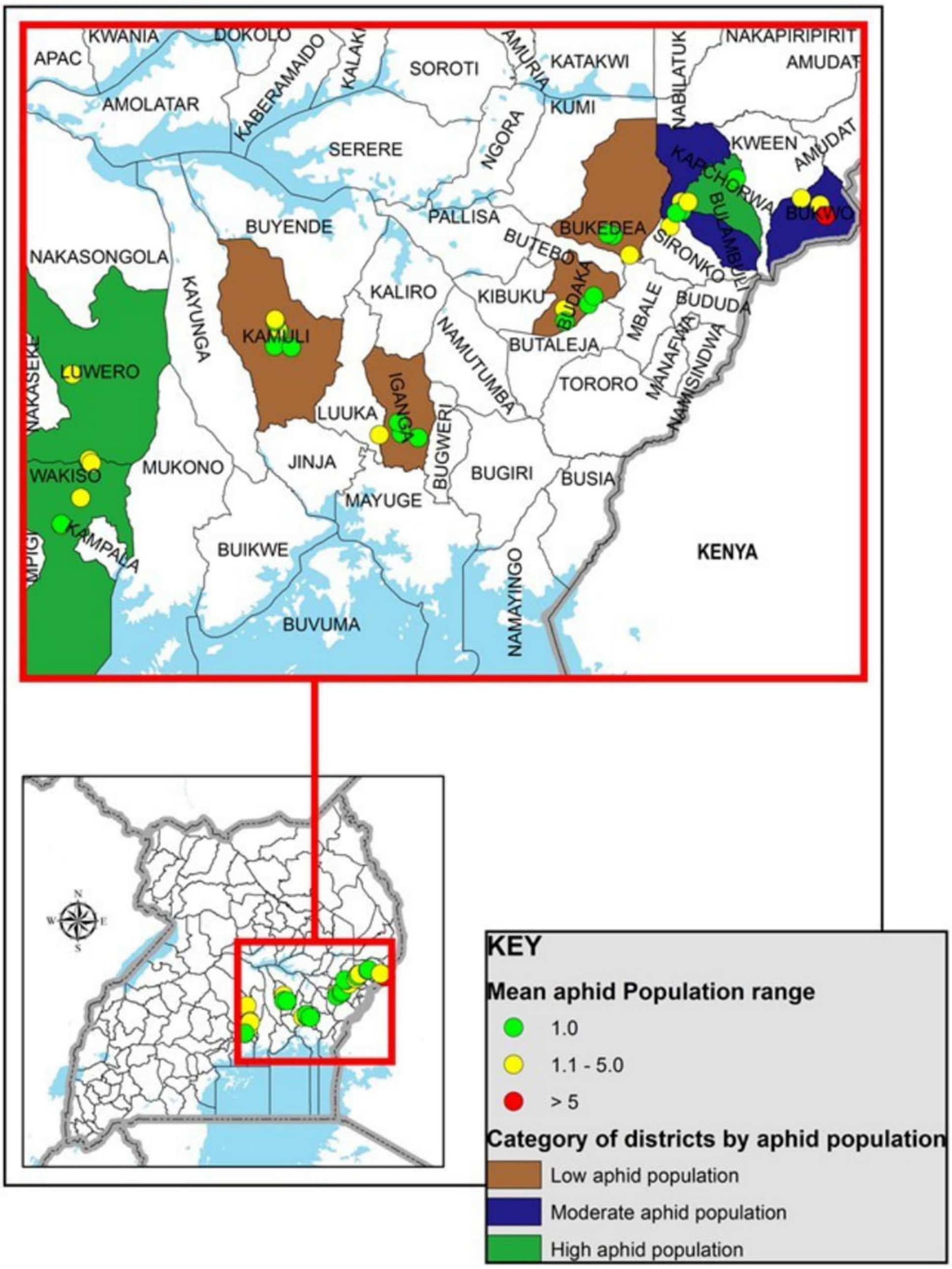

FIGURE 2
Map of Uganda showing cassava fields surveyed for aphids occurrence and sample collection. Locations where aphids were collected; Green, low aphid population in cassava fields (one aphid per plant); Yellow, moderate aphid population (two to five aphids per plant); Red, high aphid population (more than five aphids per plant).

of aphid transmission because potyviruses require a DAG motif to bind to the aphid stylet in a non-persistent transmission mode (Ateka et al., 2017). To our knowledge, this is the first record for detection of CBSIs in aphids found feeding on CBSD-symptomatic cassava plants.

Aphids were found on a wide host range of weed plants growing near cassava fields. This presents possibility of aphids moving from the weed plants to cassava and *vice versa*. RT-PCR was performed on aphids and the CBSD-symptomatic cassava leaves using the diagnostic primers reported in Mbanzibwa et al. (2011). Results confirmed that the CBSD-symptomatic cassava leaves and the aphids contained CBSIs. Such CBSIs-infected plants can be considered to be likely sources of the CBSIs that are acquired by the aphids. However, agarose gel electrophoresis of the PCR products for the CBSIs in the aphids showed faint bands compared to the distinct PCR bands observed in the CBSD-symptomatic cassava plant leaves. This may be indicative of low CBSIs titers present in the aphids as compared CBSD-symptomatic cassava plants.

Molecular characterization of the aphids targeting the mtCOI gene of insects using the primers reported by Folmer et al. (1994) gave a 700-bp PCR product and on sequencing, it was confirmed that three different aphid species were present in the

FIGURE 3
Images of aphids found on cassava plants in surveyed districts. **(A)** Aphids on leaves of a CBSD asymptomatic (healthy) cassava plant in Bukwo district. **(B)** CBSD symptomatic cassava leaves in a field in the Bulambuli district; aphids were collected in this field. **(C)** Asymptomatic cassava leaves with aphids. **(D)** Aphids on the lower side of cassava with CBSD symptoms. **(E)** CBSD symptomatic plant in Budaka district; aphids were collected from this field. **(F, G)** Aphids on the lower side of cassava leaves. **(H)** Aphid nymphs on cassava leaf.

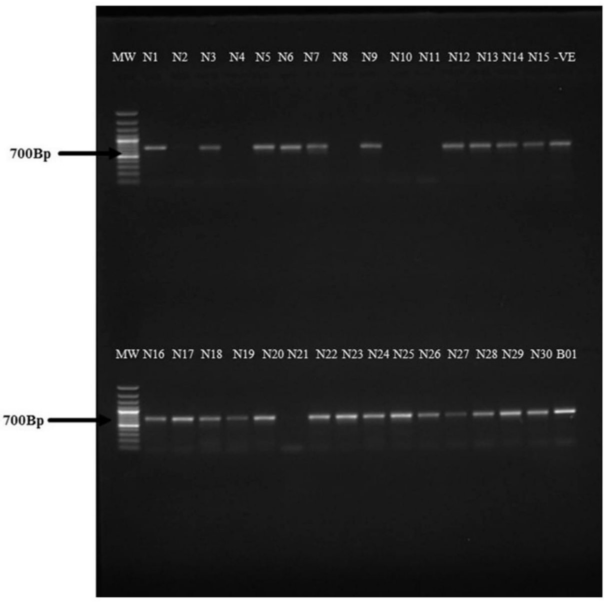

FIGURE 4
Agarose gel electrophoresis for the PCR products amplifying the mtCOI gene in aphids using the mtCOI primers HCO2198-puc (5′-TAAACTTCWGGRTGWCCAAARAATC-3′) and HCO-2198 (5′-TAAACTTCAGGGTGACCAAAAAATCA-3′). Lane 1: 1 kb MW ladder. Samples N1–N30 from different aphids collected in and around cassava fields at NaCRRI, Namulonge. Samples B01 was an aphid sample collected from a cassava plant in the Bulambuli district (Buginyanya). A 700-bp PCR product was amplified representing the mtCOI gene in the aphids.

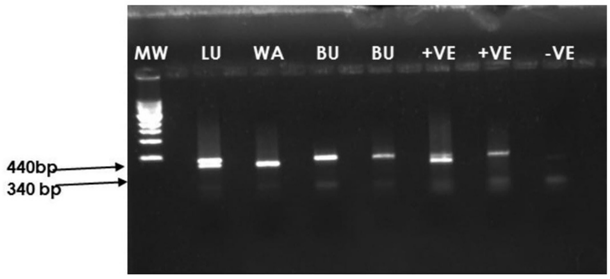

FIGURE 5
Agarose gel electrophoresis of the PCR products amplified using CBSIs diagnostic primers CBSDDF2 (5′-GCTMGAAATGCYGGRTAYACAA-3′) and CBSDDR (5′-GGATATGGAGAAAGRKCTCC-3′). Lane 1: 1 kb MW ladder. Lane 2: Cassava sample collected from Luwero (LU) district from a field with CBSD and aphids. Lane 3: Cassava sample collected from Wakiso (WA) district from a field with CBSD and aphids. Lanes 4 and 5: Cassava samples collected from the Bulambuli district (BU) from a field with CBSD and aphids. Lanes 6 and 7: Positive control. Lane 8: Negative control.

surveyed fields in Uganda. The aphids identified included *Aphis solanella*, *Aphis fabae mordvilkoi*, and *Rhopalosiphum sp* with *Aphis solanella* being the most prevalent species in the samples that were analyzed by molecular characterization (Supplementary Table 3). Previous studies have reported seasonal effect on aphid diversity and this could explain the observations on the diversity of aphids reported in this study (Wamonje et al., 2017). On the contrary, the generalist green peach aphid (*Myzus persicae*) was not observed to be present in the surveyed cassava fields. The green peach aphid has been reported to be one of the major aphid species involved in the transmission of potyviruses (Gadhave et al., 2020). Most of the sampled aphids were black winged (alate) aphids. The presence of wings on the aphids facilitates their fast movement in the field and hence presents challenges in controlling these aphids using insecticides as they keep moving from one plant to the other. These findings indicate the potential of the aphids to acquire CBSIs, but virus retention,

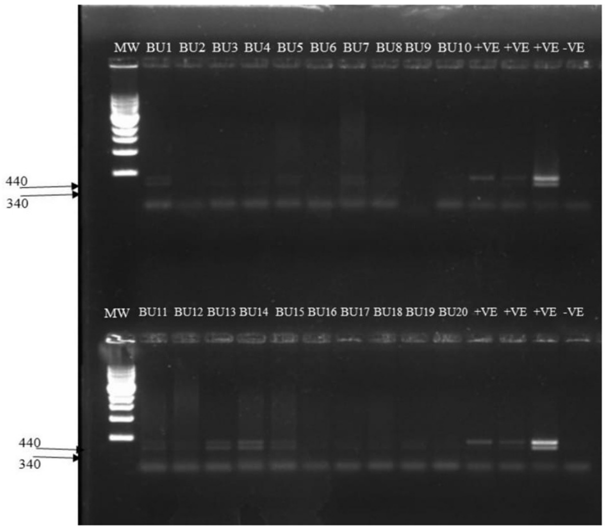

FIGURE 6
Amplification of CBSV and UCBSV in aphids using diagnostic primers CBSDDF2 (5′-GCTMGAAATGCYGGRTAYACAA-3′) and CBSDDR (5′-GGATATGGAGAAAGRKCTCC-3′). Lane 1: 1 kb MW ladder Lanes BU1-BU20: Aphid samples collected from CBSD infected fields in Bulambuli district. Double bands are indicative of mixed infection of CBSV (340 bp) and UCBSV (440 bp). Lanes labeled +ve are cassava plants from which the aphids were collected. Lane labeled −ve is the negative control.

replication, circulation, and transmission remain unknown and require further investigation.

For efficient transmission, plant viruses usually encode proteins that facilitate the virus-vector transmission process. For instance, for potyviruses, the CP and the HC-Pro act as a bridge with the host to aid in viral transmission (Ateka et al., 2017). The detection of both CBSV and UCBSV is interesting because previous reports suggest likely aphid transmission of only CBSV owing to the presence of a DAG (Asp-Ala-Gly) motif in its genome. The DAG motif is implicated in aphid transmission of potyviruses, and this has been reported to be present in the genome of CBSV, whereas that in UCBSV is DEG (Asp-Glu-Gly) (Ateka et al., 2017). It would be rather unusual for very related viruses to be transmitted by such diverse insects, as ideally it is expected that UCBSV and CBSV being related viruses, should be transmitted by the same vector (Whitfield et al., 2015). Although the DAG has been implicated in the aphid transmissibility of viruses, there have been reports were potyviruses with motifs other than the DAG motif are also aphid transmissible (López-Moya et al., 1999).

Interestingly, the DAG motif is also present in the coat protein (CP) of *Squash vein yellowing virus* (SqVYV) a member of the family *Potyviridae* and genus *Ipomovirus*, to which the cassava brown streak ipomoviruses (CBSV and UCBSV) belong. However, aphid transmission studies using *Myzus persicae* aphids in the transmission of SqVYV demonstrated that the virus was not aphid transmissible (Adkins et al., 2007). The possible explanation for the failed aphid transmission in these experiments was attributed to possibly incorrect sequence context surrounding the DAG motif (López-Moya et al., 1999) or the DAG motif occurring too far away from the N-terminus to be exposed (Shukla and Ward, 1988). With the availability of infectious clones for both UCBSV and CBSV (Duff-Farrier et al., 2018), the DAG and DEG motifs in CBSV and UCBSV infectious clones can be mutated, and aphid transmissibility studies can be performed to confirm if the motifs are necessary for aphid transmission. In conclusion, it is recommended that transmission studies are undertaken to confirm if aphids can transmit CBSIs.

Data availability statement

The generated sequence datasets for this study can be found in the GenBank under accession numbers OP223337, OP223338, OP223339, and OP223340.

Author contributions

SN: data collection, analysis, and writing the manuscript. RK: collection of data from the fields. PA: analysis of data. SB, TA, and SS: experimental design and data collection. AB: experimental design. GF: financial support. All authors contributed to the article and approved the submitted version.

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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.

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Supplementary material

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Government regulations, biosecurity awareness, and farmers' adoption of biosecurity measures: Evidence from pig farmers in Sichuan Province, China

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Introduction: To date, African swine fever (ASF) is the greatest challenge to sustainable development in the pig farming industry in Sichuan and elsewhere. Biosecurity measures adopted by farmers are an important way to prevent ASF. As a way to advocate the adoption of biosecurity measures by farmers, government regulations (GRs) can guide and promote farmers' biosecurity awareness and adoption of related measures and thereby support the sustainable development of pig farming.

Method: In this study, a theoretical framework for systematic analysis is established, and survey data of 351 pig farmers are used to estimate the effects of GRs on the farmers' adoption of biosecurity measures.

Conclusions: The main conclusions are as follows. (1) The different types of GRs all pass the significance test and promote farmers' adoption of biosecurity measures, indicating that the Chinese government's biosecurity policies at this stage are effective. (2) According to a mediation effect model, GRs can promote farmers' adoption of biosecurity measures by increasing the level of biosecurity awareness among farmers. (3) From the results of a heterogeneity test, the effects of GRs on the adoption of biosecurity measures among farmers in the low rearing income level, short rearing time and low rearing scale groups are much greater than those in the high rearing income level, long rearing time and high rearing scale groups.

Policy recommendations: Based on the above conclusions, the results of this study suggest that the government should continue to strengthen GRs, especially guided GRs, such as biosecurity measure training. Moreover, for farmers with different backgrounds, the government should adopt distinct strategies to improve the effectiveness of GRs.

KEYWORDS

government regulation, pig farmers, mediation effect model, biosecurity awareness, biosecurity measures

1. Introduction

African swine fever (ASF) is an animal disease with high infectivity and mortality (Mason-D'Croz et al., 2020). As an exotic disease, ASF has been highly disastrous to the Chinese livestock industry (Zhao, 2019; Yao et al., 2022). According to the National Bureau of Statistics of China (NBS, 2022), in 2019, pig production in the country declined severely to 310.41 million heads, representing a 27.5% decline from 2018 (NBS, 2022). Within a short period, ASF spread to all regions of mainland China, and most farmers were forced to stop production or reduce the scale of pig farming (Xu et al., 2022; Yao et al., 2022). The shortcomings of biosecurity prevention and control in the pig farming industry have been revealed. Biosecurity measures are essential for maintaining healthy farms (Horrillo et al., 2022). Therefore, it is important to promote farmers' adoption of biosecurity measures to sustainably develop the pig farming industry (Xu et al., 2022).

Government regulations (GRs) are the main measures to regulate farmer behaviors (Zhao et al., 2018). Since the emergence of ASF in northeastern China at the end of 2018, the Chinese government has issued several successive notices to slow the destructiveness of the disease. These policies include the Notice of the General Office of the State Council on Doing a Good Job in the Prevention and Control of ASF and Other Animal Diseases and the Notice of the Ministry of Agriculture, and Rural Affairs on Printing and Distributing Eight Bans on the Prevention and Control of ASF. However, because of the high transmission and mortality and the weak biosecurity control abilities of farmers, biosecurity control has not been visibly effective. From 2019 to 2021, the Chinese government issued policies to improve farmer biosecurity prevention and control capabilities, including the Opinions on Strengthening the Prevention and Control of ASF, ASF Emergency Implementation Plan (2019 Edition), ASF Emergency Implementation Plan (2020 Edition), and Technical Guidelines for Normalized Prevention and Control of ASF (Trial Version). In 2021, ASF was successfully controlled in China, and the yield of pigs in that year reached 670 million heads, returning to the level of a normal year (2017). The Chinese government has made great contributions to the prevention of ASF. Therefore, a full understanding of the role of Chinese government regulations in farmers' adoption of biosecurity measures has tremendous implications for other countries experiencing ASF.

ASF is devastating to the pig industry; improving the biosecurity behaviors of farmers has become a popular topic. Xie (2022) conducted a study on whether policy insurance is conducive to farmers recovering lost pig production based on 360 questionnaires in Jiangsu Province, China; the researchers found that compensation encourages farmers to adopt biosecurity measures to a certain extent. However, Beach et al. (2007) believes that there is a certain substitution relationship between government compensation and farmers' biosecurity input, leading to the deviation of farmers' behaviors from policy goals and creating adverse incentives. The reason for this phenomenon may be that farmers' biosecurity behavior or incentive policies distort market signals, reducing decision-making motivation due to information asymmetry (Bicknell et al., 1999). In addition, some scholars have discussed the factors that affect the biosecurity behaviors of pig farmers. Sahlström et al. (2014) found that farmers' sex, age, education level, and risk preference have positive effects on biosecurity behaviors. Other scholars have found that the scale of rearing, the standardization of pig farm facilities, and the content of training play important roles in the prevention of disease and the control of farmers' biosecurity (Zhang and Wu, 2012; Wu et al., 2015; Hennessy and Wolf, 2018). Although there are some studies on the biosecurity behaviors of farmers in the literature, some inadequacies remain. Firstly, there are many types of GRs, and the effects of GRs on the behaviors of pig farmers are not fully explained from a single perspective; thus, deeper discussion is necessary. Secondly, the literature rarely discusses the influence mechanism of GRs on the adoption of biosecurity measures by pig farmers, while improving the effectiveness of GRs is an important way to ensure the sustainable development of the pig farming industry.

To date, ASF is still the biggest challenge for the sustainable development of the pig farming industry. Many countries have invested large amounts of money and specialized technical staff to address ASF. Therefore, it is valuable to study whether GRs effectively promote farmers' adoption of biosecurity measures. The main objective of this study is to analyze the mechanisms and interventions by which GRs influence farmers' adoption of biosecurity measures to improve the sustainable development of the pig farming industry. The specific goals include (1) to theoretically reveal the influence mechanism of GRs on farmers' adoption of biosecurity measures; (2) to empirically analyze the effects of GRs (including different types of GRs) on the adoption of biosecurity measures by pig farmers by using survey data; (3) to test the mediating effect of biosecurity awareness of pig farmers; and (4) to analyze the role of GRs in the adoption of biosecurity measures by pig farmers in different farming contexts. There are three marginal contributions. Firstly, we use microsurvey data to analyze the impacts of GRs on farmers' adoption of biosecurity measures, providing insights for government decision-making. Secondly, we use a mediation effects model to analyze the transmission mechanisms by which GRs influence farmers' adoption of biosecurity measures, contributing to an in-depth understanding of methods to promote farmers' adoption of biosecurity measures. Third, grouping regressions are used to test the heterogeneous effects of GRs on biosecurity measures adopted by farmers with different backgrounds, which can help government policy become more targeted and effective.

2. Theory and hypothesis

2.1. GRs and farmers' adoption of biosecurity measures

As economic agents, farmers' biosecurity behaviors have great externalities in their biosecurity behaviors (Brennan and Christley, 2013). Ellis-Iversen et al. (2010) and Brennan and Christley (2013) argued that in the processes of farming production and disease prevention and control, some farmers have refused to implement biosecurity measures; thus, they sell infected livestock to reduce costs and obtain high returns, harming the interests of other farmers and generating large negative externalities (Ellis-Iversen et al., 2010; Annes and Bessiere, 2018). In practical production, pig farmers are limited rational agents (Liu, 2021).

Abbreviations: African swine fever, ASF; Government regulations, GRs; guided government regulations, GGRs; incentive government regulations, IGRs; constraint government regulations, CGRs; policy awareness, PA; value awareness, VA; content awareness, CA; education level, EL; the labor force of the farming family, LF; rearing time, RT; rearing scale, RS; the rearing income as a proportion of the total household income, RIS; standardized farm, SF; cooperative organization, CO; rearing insurance, RI; farmers' adoption of biosecurity measures, FABM; National Bureau of Statistics of China, NBS.

If the cost of adopting biosecurity measures greatly exceeds the sales revenue of farmers, it is difficult for pig farmers to choose to focus on biosecurity issues. Therefore, the resulting negative externalities require government intervention (Zhou et al., 2022). To maximize utility in the decision-making process, the sum of utilities obtained by farmers adopting biosecurity measures, without considering external factors, is expressed as follows (1):

$$\Delta U_1 = (U_T + U_{PE} - U_{C1}) \tag{1}$$

where ΔU_1 is the total utility obtained by the adoption of biosecurity measures by a farmer without considering external factors; U_T is the utility gained from the production improvement (T) due to the adoption of biosecurity measures ($U_T \geq 0$ as an increasing function of T); U_{PE} is the utility of the positive externality (E) gained by farmers adopting biosecurity measures ($U_{PE} \geq 0$ and is an increasing function of E); U_{C1} is the reduced utility due to the cost of adopting biosecurity measures (C_1, $0 \leq C_1 \leq$ BDG, where BDG is a budget constraint for farmers; $\Delta U_1 \geq 0$ is an increasing function of C_1). When $U_1 > 0$, the farmer adopts biosecurity measures; otherwise, these measures are not adopted.

By considering external institutional factors, the utility of farmers' adoption of biosecurity measures includes the government benefits received. Then, the utility obtained by the farmer is expressed as follows (2):

$$\Delta U_2 = (U_T + U_{PE} + U_S) - (U_{C1} + U_{C2} + U_L) \tag{2}$$

where ΔU_2 is the total utility obtained by farmers adopting biosecurity measures considering external institutional factors; U_S is the utility of government support (S) received by farmers for adopting biosecurity measures ($U_S \geq 0$, which is an increasing function of S); U_{C2} is the reduced utility ($U_{C2} \geq 0$, which is an increasing function of C_2) of government penalties (C_2, $0 \leq C_2 \leq$ BDG) for biosecurity risks caused by farmers who do not adopt biosecurity measures, such as the unreasonable disposal of breeding waste and the sale of dead pigs; and U_L is the utility loss caused by the biosecurity risk.

GRs include three dimensions: guided government regulations (GGRs), incentive government regulations (IGRs), and constraint government regulations (CGRs) (Ajzen, 1991; Zhu et al., 2021). In the context of farmers' biosecurity measures, GGRs describe regulations by which the government conducts various activities, such as publicity, promotion, and training, related to disease prevention and control of pig production to enhance farmers' biosecurity awareness. This approach enables farmers to realize the economic benefits created by adopting biosecurity measures (U_T and U_{PE} increase while U_L decreases), and reduce pig farmers' information collection and technical learning costs (U_{C1} decreases), thereby increasing the adoption of biosecurity measures. IGRs include regulations in which the government reduces the cost of safe production (C_b) for farmers by providing subsidies to ensure that they receive minimum compensation and to promote their expected benefits. Under these measures, the actual expenditure of farmers adopting biosecurity measures is C_r ($C_r = C_1 - C_b$), and the cost–utility of adopting biosecurity measures for farmers decreases to U_{Cr}. Therefore, the utility obtained by the farmer is $\Delta U_2{'} = (U_T + U_{PE} + U_S) - (U_{Cr} + U_{C2} + U_L)$. Because $C_1 > C_r$, $U_{C1} > U_{Cr}$, and $\Delta U_2{'} > \Delta U_2$, thus, $P(\Delta U_2{'} > 0) > P(\Delta U_2 > 0)$. CGRs encompass regulations in which the government restricts the production measures available to farmers by promulgating relevant laws and policies and increasing the degree of punishment for illegal activities. Pig farmers that do not adopt biosecurity measures are punished (C_2) for unreasonable biosecurity risks caused by abusing veterinary drugs and randomly disposing of infected or dead pigs, increasing U_{C2}. Therefore, for government constraints, the cost for farmers likely increases. To reduce the cost of violations, farmers must comply with the relevant GRs. Therefore, we propose the following hypothesis (H1):

H1: GRs are conducive to promoting farmers' adoption of biosecurity measures, and IGRs, CGRs and GGRs have the same promoting effect.

2.2. GRs, biosecurity awareness, and farmers' adoption of biosecurity measures

According to the theory of planned behaviors (Ajzen, 1991), the decision-making of the agent is a dynamic process in which the agent forms their awareness by collecting and screening information, guiding their behavioral responses (Lin et al., 2018). Biosecurity awareness refers to a subject's understanding of specific information, government policies, and safety values; this aspect has an important impact on the overall prevention and control of animal diseases (Breen et al., 2013). In this paper, farmers' awareness of biosecurity behaviors refers to their understanding of biosecurity policies, information, and values. As the main body of biosecurity behaviors, the farmers' biosecurity awareness level is the basis for promoting the adoption of biosecurity measures (Xu et al., 2022). Farmers' biosecurity awareness reflects whether they understand methods for maintaining the biosecurity situation of the farm and whether they have a sense of responsibility for this action. The expansion of farmers' awareness of biosecurity may help guide the emergence of biosecurity behaviors among farmers (Qiao and Zhang, 2019). Based on the above analysis, we propose the following hypothesis (H2):

H2: Biosecurity awareness can encourage farmers to adopt biosecurity measures.

GRs may affect farmers' adoption of biosecurity measures by increasing their biosecurity awareness. Due to the limitations of age and education experience, it is difficult for most farmers in China to learn biosecurity knowledge and skills without assistance (Yu and Yu, 2019). To improve farmers' productivity and revive the industry, the government has formulated biosecurity prevention and control policies, conducted awareness training, and monitored and disciplined farmers (Toma et al., 2013). These actions can guide farmers to understand pig farming and biosecurity policies, regulate their production behaviors, and reduce biosecurity risks (David et al., 2021). This information leads to the following hypothesis (H3):

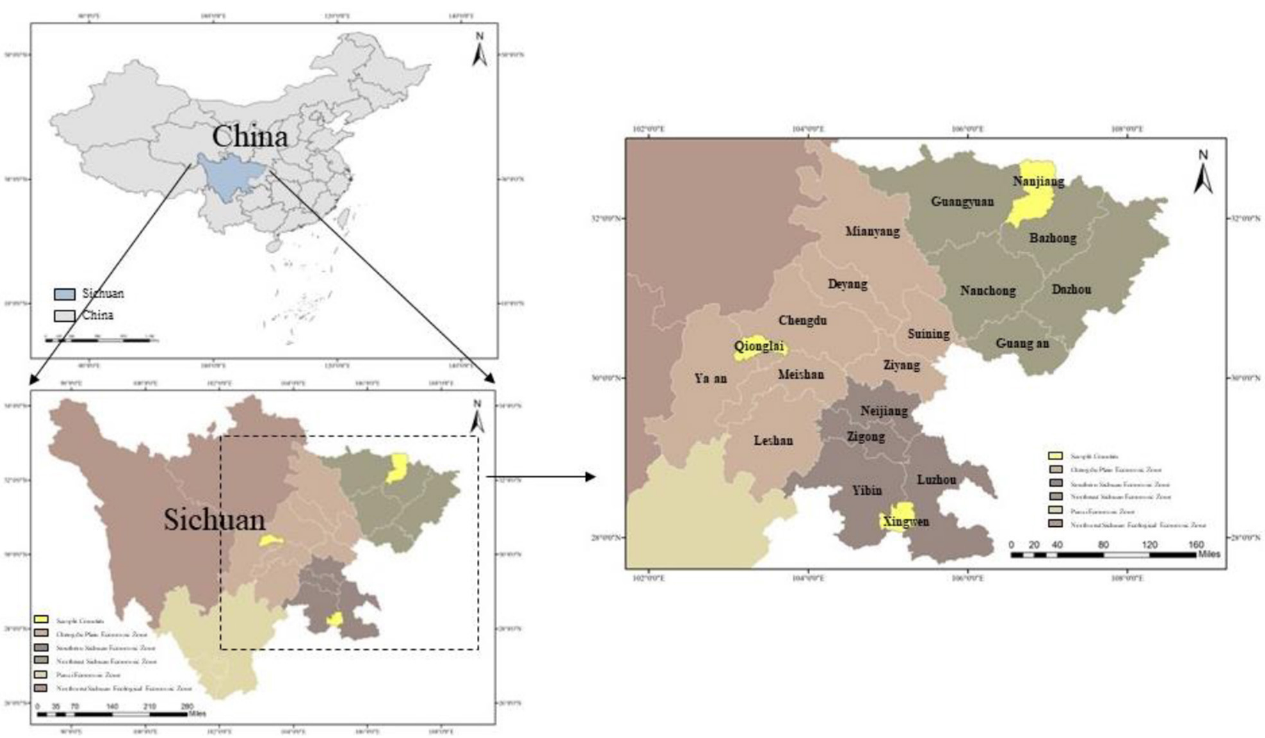

FIGURE 1
Location map of sample counties.

H3: GRs promote the adoption of biosecurity measures by enhancing farmers' biosecurity awareness.

3. Materials and methods

3.1. Data source

Sichuan Province is a major pig production area in China and has been ranked among the top regions for pig production for many years (Wang et al., 2015). Before the outbreak of ASF, the pig rearing volume in Sichuan Province reached 43.77 million heads in 2017, accounting for ∼10% of the national total (NBS, 2022). After the spread of ASF in Sichuan Province, government departments provided substantial support to resume pig rearing, enabling the province to recover pig production capacity. According to the NBS, in 2020, the number of pigs reared in Sichuan Province reached 56.14 million heads, accounting for 10.65% of the total number in the country and ranking first in China. Moreover, Sichuan Province's economic development conditions and rearing environment exhibit obvious stepped characteristics. For example, the levels of economic development and rearing technology are relatively high in the central plain and relatively low in the hilly and plateau areas. These factors have a certain influence on the implementation of government policies and the biosecurity behaviors of farmers, which better represent the production recovery of farmers at different levels. Therefore, we take Sichuan Province as the field investigation area in this paper.

The research method involved one-on-one household interviews in Sichuan Province from June to September 2021. The sample selection of farmers was based on the principle of combining purposive, stratified and random sampling. The specific sampling investigation process was as follows. Firstly, according to regional characteristics, Sichuan Province was divided into five regions: the Chengdu plain economic zone, southern Sichuan economic zone, northeast Sichuan economic zone, Panxi economic zone, and northwest Sichuan ecological economic zone. We chose the Chengdu plain economic zone, southern Sichuan economic zone and northeast Sichuan economic zone for investigation. These three regions have a greater concentration of pig farms and have the largest number of pigs (Wang et al., 2015). Then, 1 large pig rearing county was randomly selected from each region. Secondly, to maximize the validity and representativeness of the sample, we interviewed regional agricultural departments and technical extension officers to gain a more detailed understanding of the development of the pig farming industry in the study area (Xu et al., 2022). According to expert suggestions, we selected the three towns with the largest rearing volume and randomly selected 40–50 pig farmers. We completed a total of 370 questionnaires through a survey. After screening and eliminating important data that were missing and inconsistent from questionnaires, a total of 351 valid questionnaires were obtained, for an effective rate of 94.86%. A map of the sample locations is shown in Figure 1.

Table 1 shows the basic information of the surveyed farmers. Among the sample, in terms of individual basic characteristics,

TABLE 1 Basic information about sample farmers.

Variables	Characteristic	Observes	Rate	Variables	Characteristic	Observes	Rate
Sex	Male	269	76.64%	Rearing insurance	Purchased	257	73.22%
	Female	82	23.36%		Not purchased	94	26.78%
Age	<40	67	19.09%	Rearing time	<10 years	115	32.76%
	40–59	254	72.36%		10–19 years	135	38.46%
	60>	30	8.55%		>20 years	101	28.77%
Education experiences	Elementary school and below	151	43.02%	Rearing scale	30–99 pigs	217	61.82%
	Junior high school	141	40.17%		100–999 pigs	119	33.90%
	High school/technical secondary School	44	12.54%		>1,000 pigs	15	4.27%
	Higher education (undergraduate and junior college)	15	4.27%	Rearing income as a proportion of total household income	<25%	6	1.71%
					25–49%	98	27.92%
Production organizations	Participation	42	11.97%		50–75%	81	23.08%
	No participate	309	88.03%		>75%	166	47.29%

The values in the "Observations" column indicate the number of samples observed with a particular characteristic, and the values in the "Rate" column indicate the proportion of the observations of a specific character to the total number of samples.

269 male farmers were interviewed, accounting for 76.64% of the total sample. Most farmers were between 40 and 59 years old; the education level of farmers was mainly junior high school and below in the total sample, accounting for 83.19%. Concerning production and operation, 67.24% of the pig farmers had been raising pigs for more than 10 years. Most farmers had raised fewer than 100 pigs (61.82%), and their rearing income exceeded 50% (70.37%) of the total household income. This finding was consistent with the fact that pig farming in rural areas in China is dominated by males and middle-aged and elderly people with a low overall education level on small- and medium-sized farms. In addition, only 11.97% of the interviewed farmers who participated in the production organization were among the 73.22% of farmers who purchased rearing insurance.

3.2. Selection of variables

3.2.1. Explained variable

In this study, we selected the farmers' adoption of biosecurity measures (FABM) as the explained variables and expressed them in terms of the number of biosecurity measures adopted by farmers. According to Center People's Government of the People's Republic of China (2010) issued by the Ministry of Agriculture Rural Affairs of the People's Republic of China (2010) and the research of Zhou et al. (2020) and Bai et al. (2012), we selected 15 core biosecurity measures: site selection and layout of pig farms, foreign personnel and vehicle management, entry and exit management of carrying items, introduction and isolation management, all-in and all-out farming, optimized management of rearing environment, clean and dirty management, food and drug storage management, rational use of veterinary drugs, regular epidemic prevention management of inputs (feed, drinking water, and drug), anti-mosquito, rat and bird facilities, internal disinfection management of pig farms, farm management record file, separate rearing of sick pigs in farms, and regular epidemic prevention and management of pigs. We categorized the number of biosecurity measures adopted by farmers into five categories, with farmers adopting 1–3 biosecurity measures being assigned a value of 1, farmers adopting 4–6 biosecurity measures being assigned a value of 2, farmers adopting 7–9 biosecurity measures being assigned a value of 3, farmers adopting 10–12 biosecurity measures being assigned a value of 4, and farmers adopting 13–15 biosecurity measures being assigned a value of 5.

3.2.2. Explanatory variables

The core explanatory variables of this paper are GRs, including (1) GGRs, which include the number of biosecurity trainings organized by the government as a proxy variable; (2) IGRs, which include the amount of government subsidy funds as a proxy variable; and (3) CGRs, which include the intensity of government supervision on farms as a proxy variable.

3.2.3. Mediation variables

The mediation variable in this paper is biosecurity awareness, including (1) policy awareness (PA), using farmers' understanding of biosecurity Technical Guidelines for the MOA (2020) as a proxy indicator; (2) value awareness (VA), using farmers' value awareness of biosecurity behaviors to prevent and control epidemic diseases as a proxy indicator; and (3) content awareness (CA), using farmers' understanding of the content and requirements of farm biosecurity management as a proxy indicator.

3.2.4. Control variables

Based on Li et al. (2014) and Wang et al. (2016), we select the factors affecting farmers' adoption of biosecurity measures from two aspects: the basic characteristics of farmers and the

TABLE 2 Descriptive statistical characteristics of variables.

Variable name	Definition	Mean	Standard deviation
Explained variable			
Farmers' adoption of biosecurity measures (FABM)	Number of farmers adopting biosecurity measures	2.883	0.892
	Farmers adopt 1–3 kinds of technology = 1; 4–6 kinds = 2; 7–9 kinds = 3; 10–12 kinds = 4; 13–15 kinds = 5		
Core explanatory variables			
Government regulations (GRs)	Calculated by entropy method	0.857	0.805
Guiding government regulations (GGRs)	Number of trainings on biosecurity prevention and control organized by the government	0.929	0.874
	Less than 1 time = 0; 1–3 times = 1; 4–6 times = 2; more than 6 times = 3		
Incentive government regulation (IGRs)	Amount of government subsidies	0.459	0.893
	None = 0; 1–1,000 yuan = 1; 1,001–2,000 yuan = 2; more than 2,000 yuan = 3		
Constraint government regulation (CGRs)	Number of on-site supervisions and inspections by government personnel in the past year	0.949	0.915
	Less than 1 time = 0; 1–3 times = 1; 4–6 times = 2; more than 6 times = 3		
Mediation variables			
Policy awareness (PA)	Do you know the Technical Guidelines for Normalized Prevention and Control of ASF (Trial)?	0.825	0.495
	Don't know = 0; know = 1		
Content awareness (CA)	Do you understand the process or requirements of farm biosecurity management?	0.718	0.451
	Don't know = 0; know = 1		
Value awareness (VA)	Do you think that the most effective method for preventing and controlling animal diseases is to exceed in the biosecurity management of farms?	0.809	0.394
	No = 0; yes = 1		
Control variables	**Basic characteristics of farmers**		
Sex	Female = 0; male = 1	0.766	0.424
Age	Under 40 = 1; 40–59 = 2; 60 and over = 3	1.895	0.516
Education level (EL)	Elementary school and below = 1; junior high school = 2; high school/technical secondary school = 3; college and above = 4	1.786	0.843
Labor force of the farming family (LF)	Number of household laborers engaged in farming	1.632	0.759
The characteristics of production and operation			
Rearing time (RT)	Less than 10 years = 1; 10–19 years = 2; 20 years and above = 3	1.96	0.785
Rearing scale (RS)	30–99 pigs = 1; 100–999 pigs = 2;1000 pigs and above = 3	1.425	0.575
Rearing income as a proportion of total household income (RIS)	0–25% = 1; 26–50% = 2; 51–75% = 3; 76% and above = 4	3.16	0.893
Standardized farm (SF)	Is it a standardized farm?	0.068	0.253
	No = 0; Yes = 1		
Cooperative organization (CO)	Did you participate in cooperative organizations?	0.120	0.325
	No = 0; Yes = 1		
Rearing insurance (RI)	Did you buy rearing insurance?	0.732	0.443
	No = 0; Yes = 1		

characteristics of production and operation. Among these aspects, the basic characteristics of farmers include sex, age, education experiences (EE), and the labor force of the farming family (LF). The characteristics of production and operation include rearing time (RT), rearing scale (RS), rearing income as a proportion of the total household income (RIS), whether the farm is a standardized farm (SF), whether the farmers have joined a cooperative organization (CO), and whether they buy rearing insurance (RI). Table 2 shows the descriptive statistical characteristics of the variables.

3.3. Model construction

3.3.1. Benchmark regression models

The number of biosecurity measures adopted by farmers is an ordinal variable, an O-logistic model used to analyze the impact of GRs on farmers' adoption of biosecurity measures. The specific equation is as follows.

$$y_i^* = \alpha + \beta_1 GR_i + \beta_i x_i + \varepsilon_i \quad (3)$$

$$y_i = \begin{cases} 1, when\ y_i^* \leq \lambda_1 \\ 2, when\ \lambda_1 < y_i^* \leq \lambda_2 \\ 3, when\ \lambda_2 < y_i^* \leq \lambda_3 \\ 4, when\ \lambda_3 < y_i^* \leq \lambda_4 \\ 5, when\ y_i^* > \lambda_4 \end{cases} \quad (4)$$

where y_i* is the explained variable, which represents the number of biosecurity measures adopted by farmers; GRs_i represents the GRs, when $i = 1,2,3$, GRs refer to IGRs, GGRs, and CGRs, respectively; x_i are control variables, which include the farmer's age, sex, education experience, etc.; ε_I is the random error term; β_1 and β_i are the coefficients. y_i* cannot be directly observed, so it needs to be represented by the variable y_i that can be directly observed. Let $\lambda_1 < \lambda_2 < \ldots < \lambda_{n-1}$ represent the threshold. In the case of n=5, there are 4 thresholds, and the corresponding relationship between y_i and y_i* is shown in formula (4).

3.3.2. Mediation effect model

To understand the internal transmission mechanism of the mediation effect model, we used the KHB model (Karlson and Holm, 2011; Xu et al., 2022) to decompose the total effect into direct effect and indirect effect test. The calculation process is as follows.

Suppose the linear regression model is as follows (5):

$$Y = \alpha_1 + \beta_1 X + \gamma_1 M + \delta_1 C + \varepsilon_1 \quad (5)$$

where Y is the explained variable; X is the core explanatory variable; M is the mediating variable; C is the control variable; and X affects Y through M. In this model, β_1 is the direct effect of X on Y.

To further calculate the total effect of X on Y:

$$Y = \alpha_2 + \beta_2 X + \delta_2 C + \varepsilon_2 \quad (6)$$

The indirect effect of the core explanatory variable X on the explained variable Y by affecting the mediating variable M can be expressed as:

$$\beta_3 = \beta_2 - \beta_1 \quad (7)$$

In this paper, if X affects Y^* through M, then:

$$Y^* = \alpha_1 + \beta_1 X + \gamma_1 M + \delta_1 C + \varepsilon_1 \quad (8)$$

$$Y^* = \alpha_2 + \beta_2 X + \delta_2 C + \varepsilon_2 \quad (9)$$

The direct effect can be expressed as $b_1 = \beta_1/\sigma_1$; total effect: $b_2 = \beta_2/\sigma_2$. σ_1 and σ_2 are scale parameters, which are the residual standard errors of Equations (5) and (6). At this point, the indirect effect of the logistic model can be expressed as (10):

$$b_2 - b_1 = \beta_2/\sigma_2 - \beta_1/\sigma_1 \quad (10)$$

The indirect effect is determined by the two scale parameters σ_1 and σ_2, which can be calculated by measuring the residual of the linear regression of the mediating variables on the explanatory variables.

$$R = M - (a + bX) \quad (11)$$

where a and b are linear regression coefficients, and R is the residual. Substituting R into model (6), we can obtain Equation (12):

$$Y^* = \tilde{\alpha_1} + \tilde{\beta_1} X + \tilde{\gamma_1} R + \tilde{\delta_1} C + \varepsilon_1 \quad (12)$$

$\tilde{\sigma_2} = \sigma_1$, $\tilde{\sigma_1}$ is the residual standard deviation of the above formula, and $\tilde{\beta_2} = \beta_2$. Then (13) and (14) can be calculated as follows:

$$b_2 - b_1 = \tilde{\beta_2}/\tilde{\sigma_2} - \beta_1/\sigma_1 = \frac{\beta_2 - \beta_1}{\sigma_1} \quad (13)$$

$$\frac{b_2}{b_1} = \frac{\beta_2}{\sigma_1} / \frac{\beta_1}{\sigma_1} = \frac{\beta_2}{\beta_1} \quad (14)$$

In the same way, the proportion of each coefficient can be calculated as:

$$100 \times \frac{b_2 - b_1}{b_2} = 100 \times \frac{\beta_2/\sigma_1 - \beta_1/\sigma_1}{\beta_2/\sigma_1} = 100 \times \frac{\beta_2 - \beta_1}{\beta_2} \quad (15)$$

To verify the mediation effect of the above model, it is only necessary to test the hypothesis H_0:$b_1 = b_2$, that is, to test whether $\beta_1$and β_2 are equal.

$$b_2 - b_1 = \frac{\gamma_2}{\sigma_2} b \quad (16)$$

where b is the coefficient of X to M in Equation (11), for (16) not to be 0, the direct effect of M on Y must not be 0, that is $\frac{\gamma_2}{\sigma_2} \neq 0$, and X is related to M, that is, b$\neq$ 0.

The Sobel test can be used to obtain the following test formula for the indirect effect:

$$M = \frac{\sqrt{N^2}(b_2 - b_1)}{\sqrt{a' \sum a}} \sim N(0, 1) \quad (17)$$

where a' represents the vector $(\frac{\gamma_2}{\sigma_2}, b)'$, $\sum$ is the covariance matrix variance of γ_2 and b.

4. Results

4.1. Benchmark regression analysis

To ensure the accuracy of model parameter estimation, we conduct a multicollinearity test on each variable before regression. The results show that the tolerance is much larger than 0.1, and the maximum value of VIF is 1.81; this value is much smaller than 10, indicating that there is no multicollinearity among the variables.

We use an O-logistic model to analyze the influences of GRs and biosecurity awareness levels on farmers' adoption of biosecurity measures. To further prove the robustness of the results, we use an ordered-probit (O-probit) model for analysis. The benchmark regression results (Table 3) show that the significance and direction of each variable are consistent with the regression results of the O-logistic model, indicating that the regression results are relatively robust.

TABLE 3 Benchmark regression results.

Variable type	Variable name	O-logistic	O-probit
		FABM	FABM
GRs	GGRs	0.629***	0.315***
		0.182	0.097
	IGRs	0.265*	0.145*
		0.152	0.079
	CGRs	0.487***	0.271***
		0.163	0.087
Biosecurity awareness	PA	1.332***	0.668***
		0.312	0.167
	CA	0.993***	0.523***
		0.322	0.18
	VA	−0.799**	−0.422***
		0.353	0.2
The basic characteristics of farmers	Sex	0.633**	0.334**
		0.278	0.153
	Age	0.024	0.033
		0.266	0.149
	EL	0.368**	0.185**
		0.178	0.09
	LF	0.410***	0.243***
		0.158	0.088
Production and operation characteristics	RT	0.12	0.074
		0.161	0.09
	RS	0.831***	0.462***
		0.248	0.136
	RIS	−0.178	−0.081
		0.139	0.076
	SF	1.806***	1.061***
		0.567	0.29
	CO	0.464	0.184
		0.457	0.235
	RI	0.628**	0.366**
		0.277	0.154
LR		−319.368***	−322.614***
Wald-Test		176.45***	206.23***
R^2		0.296	0.289
N		351	351

Standard errors in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

4.1.1. GRs

According to the results in Table 3, all three types of GRs passed the significance test, indicating that the top-down governance method significantly affected farmers' biosecurity behaviors. Specifically, GGRs, IGRs, and IGRs all passed the significance test ($P \leq 10\%$), and the coefficients were positive. This finding indicated that GGRs, IGRs, and IGRs played significant roles in promoting the adoption of farmers' biosecurity measures.

4.1.2. Biosecurity awareness

All three types of biosecurity awareness passed the significance test, indicating that biosecurity awareness significantly impacted farmers' adoption of biosecurity measures. Specifically, both biosecurity policy awareness and content awareness were significant at the 1% level, and the coefficients were positive. Value awareness was significant at the 1% level, but value awareness had an inhibitory effect on farmers' adoption of biosecurity measures.

4.1.3. Control variables

Sex was significant at the 5% level, and the coefficient was positive, indicating that sex played a significant role in promoting the adoption of biosecurity measures by farmers. Family labor was significant at the 10% level, and the coefficient was positive, indicating that the more laborers in the family were engaged in pig rearing, the more inclined the farmers were to adopt biosecurity measures. The rearing scale and standardized farms were significant at the 1% level, respectively, and both promoted the adoption of biosecurity measures. Rearing insurance was significant at the 5% level, and the coefficient was positive, indicating that farmers who purchased rearing insurance had higher biosecurity awareness levels and were more inclined to adopt biosecurity measures.

4.2. Mediation effect analysis

The estimation results of the benchmark model show that GRs and biosecurity awareness significantly impact farmers' adoption of biosecurity measures. On this basis, we discuss whether there is a mediating role in the influences of GRs on farmers' adoption of biosecurity measures, the relationship between the direct and indirect impact paths, and the contribution of each mediation variable to farmers' adoption of biosecurity measures. According to the results of the mediation effect test in Table 4, the overall fitting effect of the model is acceptable.

Column (1) in Table 4 shows the results of the O-logistic model without mediating variables, and columns (2)–(4) show the results of the regression tests with mediating variables. According to the test results of the mediation effect model, GRs positively affect policy, content, and value awareness levels, and all of these effects pass the significance test. Relative to column (1), there is no significant shift in the coefficients of GRs in column (5). Policy awareness, content awareness, and value awareness all pass the significance test, proving that GRs have a mediating effect on farmers' adoption of biosecurity measures. Thus, hypotheses 1, 2, and 3 are further verified.

The KHB model is further applied to decompose the effects of GRs on farmers' adoption of biosecurity measures. According to Table 5, the total effect of the model is 1.656, of which the direct effect is 1.153, the indirect effect is 0.502 and the effect is significant at the 1% level. In addition, Table 5 shows

TABLE 4 Mediation effect test results.

Variables	(1) FABM	(2) PA	(3) CA	(4) VA	(5) FABM
GRs	1.556***	1.641***	1.519***	0.629**	1.153***
	(0.194)	(0.265)	(0.296)	(0.256)	(0.205)
PA					1.478***
					(0.306)
CA					0.964***
					(0.318)
VA					−0.573*
					(0.336)
Control variables	Yes	Yes	Yes	Yes	Yes
LR	−341.553***	−158.168***	−164.609***	−155.780***	−322.423***
R^2	0.247	0.339	0.212	0.097	0.289
N	351	351	351	351	351

Standard errors in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

TABLE 5 Decomposition effects and comparison of the KHB method.

Effect type	Coefficient	Standard error	Z-Value	$P > \|Z\|$
Indirect-effect	0.502	0.102	4.94	0.00
Direct-effect	1.153	0.205	5.63	0.00
Total-effect	1.656	0.199	8.33	0.00

TABLE 6 Decomposition of the indirect effects of GRs on the farmers' adoption of biosecurity measures.

Mediation variables	Coefficient	Standard error	Indirect effect	Total effect
PA	0.465	0.100	74.98%	44.24%
CA	0.192	0.064	31.01%	18.30%
VA	−0.037	0.029	−5.98%	−3.53%

that the indirect effect accounts for 30.31% of the total effect, indicating that GRs greatly impact farmers' adoption of biosecurity measures by enhancing biosecurity awareness levels. The total, direct, and indirect effects were positive in terms of the coefficient symbol, indicating that GRs may directly promote the adoption of biosecurity measures by farmers and produce indirect positive effects through mediation variables.

According to the results in Table 6, the indirect effects of GRs through policy, value, and content awareness are 0.465, −0.037, and 0.192, respectively. Policy awareness has the largest indirect effect on farmers' adoption of biosecurity measures, accounting for 74.97% of the indirect effect and 44.24% of the total effect. The indirect effect of value awareness is minimal, and its contribution is negative, accounting for −5.98% of the indirect effect and −3.53% of the total effect; these findings are consistent with the previous results.

4.3. Robustness test

To examine the stability and reliability of the research methodology and the explanatory power of the indicators, and to prevent the estimation bias caused by certain uncontrollable factors from making the research conclusions unconvincing, based on the use of the O-probit model (Table 3), this paper further tests the robustness by replacing the core explanatory variables. The variable "government supervision intensity" is replaced with "government supervision scope on farm safety", and GR is re-measured by the entropy method. The results of the robustness test (Table 7) indicate that the core explanatory variables and mediating variables pass the significance test, and the direction of the coefficients is mostly consistent with the results in Table 4, further suggesting that the results of this study are robust.

4.4. Heterogeneity analysis

We study the mechanisms by which GRs influence farmers' adoption of biosecurity measures; however, the rearing income level, rearing time, and rearing scale of different farmers influence GRs and farmers' adoption of biosecurity measures. Therefore, we divide the rearing income level, rearing time and rearing scale into groups to further explore the impacts of GRs on farmers' adoption of biosecurity measures. We use the mean values of the rearing income level, rearing time, and rearing scale as the grouping criteria; additionally, we divide the farmers into low-mean groups (low rearing income level, low rearing scale and short rearing time) and high-mean groups (high rearing income level, high rearing scale and long rearing time). Next, we take farmers' adoption of biosecurity measures as the explained variables and GRs, IGRs, CGRs, and GGRs as the explanatory variables and use the O-logistic model to examine the contributions of different rearing income levels, rearing times, and rearing scale groups to GRs and farmers'

TABLE 7 Robustness test.

Variables	(1) FABM	(2) PA	(3) CA	(4) VA	(5) FABM
GRs	1.529***	1.464***	1.256***	1.232***	1.157***
	(0.190)	(0.253)	(0.274)	(0.271)	(0.200)
PA					1.497***
					(0.305)
CA					0.987***
					(0.318)
VA					−0.507*
					(0.339)
Control variables	Yes	Yes	Yes	Yes	Yes
LR	−341.705***	−161.869***	−169.010***	−157.649***	−321.310***
R^2	0.247	0.324	0.191	0.086	0.291
N	351	351	351	351	351

Standard errors in parentheses; $^{*}p < 0.10$, $^{***}p < 0.01$.

TABLE 8 Effects of different groups of GRs on farmers' adoption of biosecurity measures.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	RIS (low-mean)	RIS (high-mean)	RT (low-mean)	RT (high-mean)	RS (low-mean)	RS (high-mean)
	FABM	FABM	FABM	FABM	FABM	FABM
GRs	1.871***	1.277***	2.354***	1.208***	2.908***	0.704***
	0.312	0.260	0.397	0.240	0.359	0.255
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.27	0.262	0.346	0.228	0.277	0.26
LR	121.01	118.19	112.39	127.62	147.18	80.96
N	185	166	115	236	217	134

Standard errors in parentheses; $^{***}p < 0.01$.

adoption of biosecurity measures. In this paper, the rearing income as a proportion of the total household income is used to express the rearing income level of farmers.

From Table 8, the effects of GRs on farmers' adoption of biosecurity measures in the low-mean groups exceed those in the high-mean groups, indicating that GRs are more effective in the low-mean groups. Table 9 shows the effects of IGRs, CGRs, and GGRs on farmers' adoption of biosecurity measures in different groups. Notably, the results shown in Table 9 are generally consistent with those in Table 8. The coefficients of various GRs in the low-mean groups are higher than those in the high-mean groups, which further shows that the roles of GRs in the low-mean groups are more significant.

5. Discussion

ASF has brought great harm to the pig farming industry in the world, so it is of great significance to find effective solutions for the pig farming industry and residents' diets. Effectively preventing the spread of animal diseases requires government support and farmers' adoption of biosecurity measures. However, the effectiveness of GRs largely depends on farmers' acceptance of different GRs and their biosecurity awareness (Xu et al., 2023). Therefore, it is necessary to examine the mechanism of different types of GRs on biosecurity measures adopted by farmers with different backgrounds to develop more perfect biosecurity prevention and control policies. This study focused on the impact of GRs, farmers' biosecurity awareness, farmers' basic characteristics and production operation characteristics on farmers' adoption of biosecurity measures. To examine these contents, a total of 351 valid samples from pig farmers were collected and were analyzed using O-probit, mediation effect model and heterogeneity test method.

Through empirical analysis, we demonstrate that current Chinese GRs can effectively promote the adoption of biosecurity measures by pig farmers. This result shows that the recent epidemic prevention policy formulated by the Chinese government to address ASF was more effective than other measures, encouraging farmers to adopt biosecurity measures to prevent the spread of

TABLE 9 Effects of IGRs, CGRs, and GGRs on farmers' adoption of biosecurity measures in different groups.

Variables	(1) RIS (low-mean)	(2) RIS (high-mean)	(3) RT (low-mean)	(4) RT (high-mean)	(5) RS (low-mean)	(6) RS (high-mean)
	FABM	FABM	FABM	FABM	FABM	FABM
IGRs	0.423*	0.254	0.614**	0.189	0.779***	0.305
	(0.222)	(0.190)	(0.293)	(0.175)	(0.256)	(0.187)
CGRs	0.734***	0.638***	0.542**	0.689***	1.002***	0.477**
	(0.219)	(0.222)	(0.275)	(0.191)	(0.225)	(0.234)
GGRs	1.117***	0.626**	1.597***	0.632***	1.324***	0.202
	(0.263)	(0.253)	(0.367)	(0.213)	(0.253)	(0.267)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.293	0.275	0.376	0.244	0.297	0.240
LR	130.79	124.44	121.92	136.71	157.58	76.29
N	185	166	115	236	217	134

Standard errors in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

immune diseases, and protect the health of pigs. However, different types of GRs have distinctly varying roles. As shown in Table 3, GGR has the largest coefficient (0.629), while IGR has the smallest coefficient (0.265). This means that GGR plays a stronger role than IGR. According to the survey study, most of the government subsidies received by pig farmers were <1,000 yuan (Table 2), and the cost of pig mortality far exceeded this value, which might be the reason for the low role of IGR. This shows that when large-scale animal diseases occur, relying on only less subsidies is not the best way, and technical training by the government may be more conducive to the farmers' adoption of biosecurity measures.

Farmers' personal characteristics and production operation characteristics also have an impact on the adoption of biosecurity measures by farmers. We find that farmers with larger size, more labor, and more standardization are willing to adopt more biosecurity measures. As stated by Ghimire and Huang (2016), larger farmers are more inclined to adopt advanced technologies to expand their returns and protect their assets. Compared with women, male interviewees express a willingness to adopt more biosecurity measures, and the reason for this phenomenon could be that female farmers tend to be more conservative in their decision-making regarding biosecurity measure adoption (Liu et al., 2019). Farmers with rearing insurance are more likely to adopt biosecurity measures. Rearing insurance, as a vital risk management tool, improves the risk tolerance of farmers by dispersing risks (Ghosh et al., 2022). This condition allows farmers to try new technologies without worrying about the adverse consequences of these technologies, thus improving the allocation efficiency of resources (Wu and Li, 2023).

Farmers' biosecurity awareness has a significance impact on farmers' adoption of biosecurity measures. However, although pig farmers are familiar with government policies and biosecurity measures, the policy values do not seem to be effective in promoting farmers' adoption of biosecurity measures. These results are similar to those of Lanyon et al. (2015) and Frössling and Nöremark (2016); that is, although farmers seemed to believe that implementing biosecurity measures was beneficial (Sayers et al., 2013), they did not widely implement such measures. There could be several reasons for this phenomenon. The interviewed farmers were small-scale free-range farmers, and there was a difference in the biosecurity awareness levels of traditional backyard farmers and standardized large-scale farmers, and the awareness levels of the investigated farmers could deviate from the actual behaviors (Li et al., 2014). Even if the farmers recognized that biosecurity behaviors can effectively prevent and control diseases, they may not have been able to adopt biosecurity measures for production due to practical factors such as the cost of adopting measures and human resource constraints (Liu et al., 2017). Some farmers even reduced production costs by decreasing the production scale and decreasing biosecurity measures (Tian and Stephan, 2020).

In addition, government regulations are more effective for farmers with short farming time, low farming income and low farming scale. These results are similar to those of Simon-Grifé et al. (2013); that is, farmers with a larger rearing scale, higher rearing income, and longer rearing time have higher management and biosecurity awareness levels, making it difficult for the government to form an obvious incentive and play a guiding role for these farmers. In contrast, smaller-scale farmers generally lack the application of biosecurity measures and awareness (Costard et al., 2009). With the help of the government, the biosecurity behaviors of small-scale farmers will effectively improve. Moreover, we see that GGRs have the greatest impact on farmers' adoption of biosecurity measures, while IGRs have the smallest impact. This result suggests that farmers are willing to receive government training, not just sanctions and subsidies (Moya et al., 2021). Therefore, the government needs to understand the characteristics of local farmers when formulating relevant policies and it should not concentrate all subsidies on large-scale farms, especially in developing countries where there are more small-scale farmers.

Although our study provides help in promoting farmers' adoption of biosecurity measures, there are some limitations. With the dual limitations of ASF and COVID-19, it is difficult for us to conduct continuous tracking surveys to form panel data. Panel data can better identify changes in farmers' adoption behaviors toward biosecurity measures under different levels of risk. In addition, another limitation of this paper is the lack of discussion of biosecurity measure adoption behaviors in large-scale farming enterprises. The huge risk posed by ASF led to many small-scale farmers withdrawing from the farming industry, thus rapidly increasing the number of large-scale farming enterprises. These farming enterprises have more capital and advanced technology and are able to provide technical and financial assistance to small-scale farmers. Therefore, future scholars should adopt panel data to analyze the factors influencing farmers' adoption of biosecurity measures. It can also focus on whether large-scale pig farming enterprises can generate technical and economic spillover effects for surrounding small-scale farmers. We believe that more in-depth studies can provide better empirical evidence for the sustainable development of pig farming.

6. Conclusion and policy recommendations

We use survey data from 351 pig farmers to investigate the transmission mechanisms and heterogeneity characteristics of the effects of GRs on farmers' adoption of biosecurity measures. The main conclusions are as follows. (1) According to the benchmark regression results, we demonstrate that GRs positively impact farmers' adoption of biosecurity measures. Furthermore, the three types of GRs—IGRs, GGRs, and CGRs—all promote the adoption of biosecurity measures by pig farmers; this finding indicates that the Chinese government's biosecurity measures at this stage are effective. (2) Through the mediation effect test, GRs can promote the adoption of biosecurity measures by enhancing farmer biosecurity awareness. Among these roles, the indirect effects of policy awareness and content awareness are more significant, while value awareness does not contribute significantly. (3) From the results of the heterogeneity test, we find that the effects of GRs on farmer biosecurity behaviors in the low-mean groups (low rearing income level, low rearing scale, and short rearing time) are considerably greater than those in the high-mean groups (high rearing income, high rearing scale, and long rearing time).

According to the research conclusions, to further strengthen the biosecurity prevention and control capabilities of farmers and to promote sustainable development in the pig farming industry, we propose the following policy recommendations. (1) The government should continue to strengthen GRs, especially GGRs, because they have the greatest positive impact on farmers' adoption of biosecurity measures. For example, the government can establish a biosecurity prevention and control information platform to share measures and technologies. (2) The government should reasonably guide farmers' awareness levels of policies and biosecurity behaviors and actively promote farmers' adoption of biosecurity measures. To mitigate farmers' fear of ASF, good publicity by government department staff and veterinarians is needed. (3) The government should strengthen the guidance and incentives for small-scale farmers to maximize the efficiency of government biosecurity measures.

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

JL and MY: conceptualization and software. MY and KZ: methodology, formal analysis, and data curation. MY and HW: validation. KZ and HW: resources. JL: writing—original draft preparation. JL and KZ: writing—review and editing and supervision. MY: visualization. JL and HW: funding acquisition. All authors contributed to the article and approved the submitted version.

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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.

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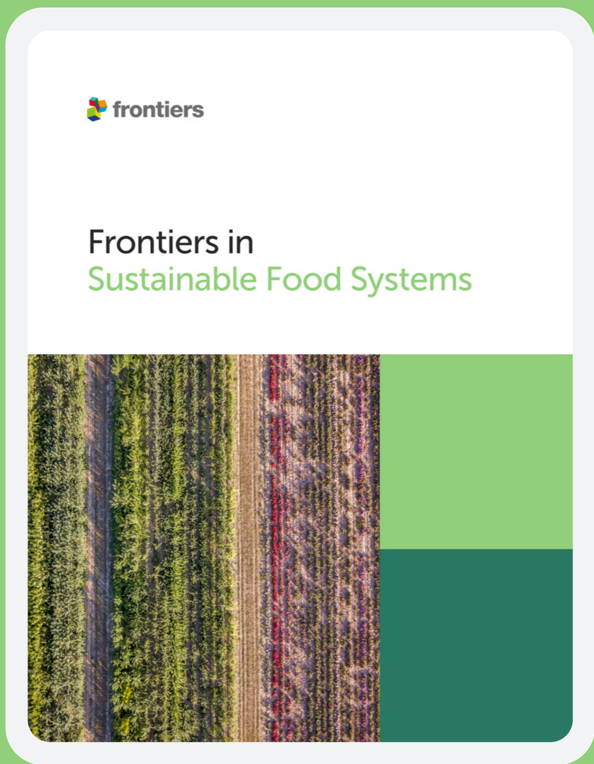

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