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Increasing resilience and adaptability to climate change of vulnerable groups in agriculture

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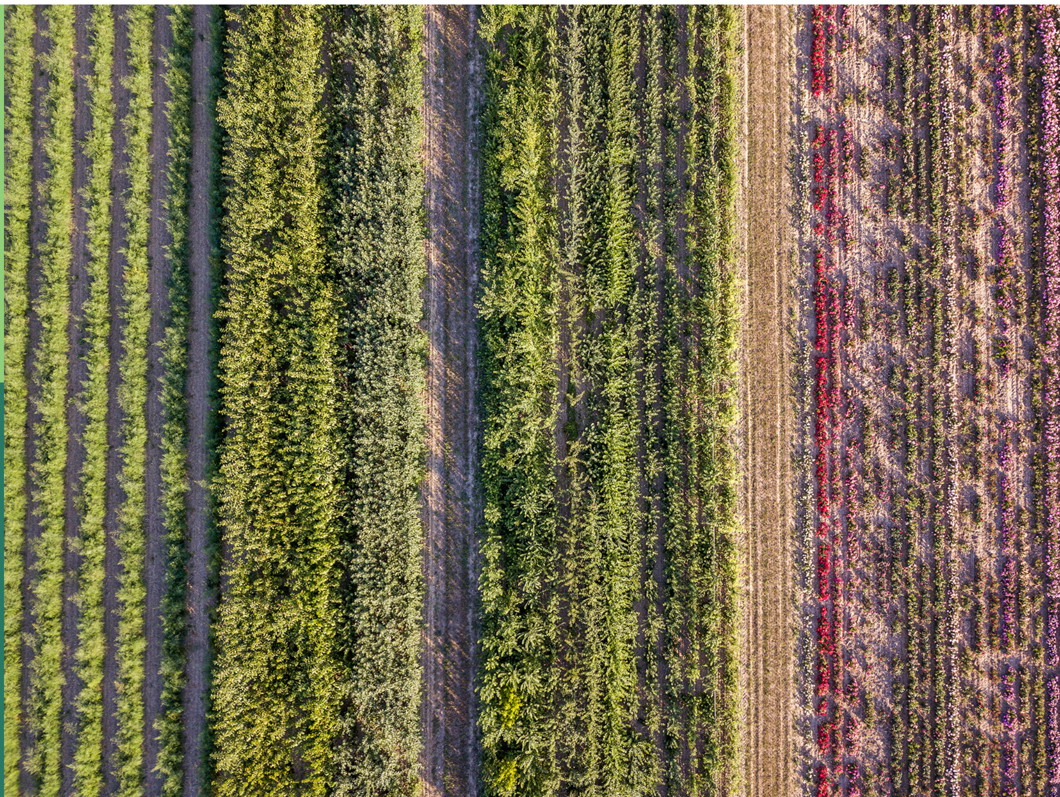

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Increasing resilience and adaptability to climate change of vulnerable groups in agriculture

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Editorial: Increasing resilience and adaptability to climate change of vulnerable groups in agriculture

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Editorial on the Research Topic
Increasing resilience and adaptability to climate change of vulnerable groups in agriculture

Introduction

Climate change continues to be a global concern because it threatens livelihoods, particularly those of society's marginalized or vulnerable populations. Despite contributing the least to climate change, developing countries are the most susceptible to its effects. This vulnerability stems from the fact that rain-fed agriculture is the primary source of livelihood for the majority of the population and poor households spend more than 60% of their income on food (Osei et al., 2024). Besides, investment in agriculture remains low with only 4% of the total agricultural lands under irrigation, particularly in sub-Saharan Africa. Other developing regions such as Asia and Latin America have 37 and 14% of their total cultivated lands under irrigation, respectively (International Center for Biosaline Agriculture, 2021).

As a result, these, primarily smallholder farmers, lack the institutional, technological, infrastructural, and economic capacity to adapt to climate change. Furthermore, the bulk of the resource-poor youth work in agriculture, making them more exposed to the effects of climate change. Recent climate change scenarios have predicted significant declines in staple food yields due to drought, high temperatures, rainfall variability, and a projected overall decline in agricultural revenue. These estimated negative consequences would directly impact food security, leaving millions of households malnourished.

According to the Food and Agriculture Organization (FAO) of the United Nations, between 720 and 828 million people worldwide are already experiencing chronic hunger. In addition, around 161 million children under the age of five suffer from stunting. In light of the uncertain climate, achieving food and nutrition security will require a radical transformation of the world's food and agricultural systems. Systems of this kind need to combat climate change, maintain the sustainability of ecosystems, increase crop yield, and help farmers become more resilient and adaptable to environmental shocks. To guarantee food equity, climate-resilient, and sustainable food system interventions that focus on the most vulnerable segments of society are required. This Research Topic focused on articles that analyzed the development of sustainable climate-resilient pathways for smallholders and other vulnerable groups in agriculture.

In all, eleven of the twenty-four manuscripts received were published after undergoing rigorous editorial and peer review processes. The articles in this Research Topic fall under three topic themes: (i) determinants of smallholder farmers' adoption of climate-smart agricultural practices, (ii) promoting the development of climate-resilient crop varieties, and (iii) effectiveness of initiatives to build resilience against climate change.

Determinants of smallholder farmers' adoption of climate-smart agricultural practices

Climate-smart agricultural practices (CSAs) refer to a set of farming techniques intended to build the resilience of farmers and sustainably enhance productivity amidst climate uncertainties. These practices include rotational cropping with legumes, mulching, zero or minimal tillage, use of compost/organic fertilizer, and planting nitrogen-fixing trees on the farm to serve as windbreaks among others. Governments, non-governmental organizations (NGOs), and other development partners have made efforts to encourage farmers to adopt CSAs, especially in areas vulnerable to climate change. However, empirical evidence suggests that the rate of adoption remains low (Nkansah et al., 2021; Iqbal et al., 2022). Recent studies have, therefore, investigated the factors that influence farmers' adoption decisions about CSAs. According to Yiridomoh et al., extension contacts, credit access, availability of climate information, and household asset holding capacity were the most important factors in farmers' decisions to adopt SCAs in the Lawra District of Ghana's Upper West region. A related study by Asante et al. further revealed that off-farm income, household size, credit, education, extension services, and gender of the farmers were factors that determined the adoption of CSAs in Ghana. Jabbar et al. demonstrated that the formation of collective farmer action groups in rural areas of Punjab, Pakistan, encouraged the adoption of CSAs. Nonetheless, membership in the action groups was influenced by farmers' risk perception, peer pressure, education, and credit access.

Promoting the development of climate-resilient crop varieties

Many researchers have argued that the use of climate-resilient crop varieties (e.g., draught tolerant, early maturing, flood-tolerant, etc.) remains the most viable option for managing the impact of climate change, particularly in vulnerable regions across the globe. According to a review of pertinent studies conducted by Shah et al., Africa lags behind in the development of flood-tolerant rice varieties. The authors discovered that the majority of rice producers in Africa's flood-prone areas were unaware of the existence of such rice cultivars. It was further suggested that using plant growth-promoting rhizobacteria (PGPR) could be a reliable approach to increasing crop growth and yield in changing climates. In a related review across Africa, Mwakyusa et al. revealed that information about newly developed crop varieties (stress-tolerant, flood-resilient, etc.) is scarce, forcing farmers to rely on indigenous cultivars. They emphasized the importance of stepping up efforts to screen and identify flood-tolerant rice varieties in Africa. Annor and Badu-Apraku conducted a field experiment in Nigeria to discover stress-resistant quality protein maize (QPM) inbred lines for hybrid development and to examine the relationship between grain yield and other researched parameters. The experiment revealed that about 60% of the QPM inbreds assessed had various levels of tolerance to drought and low nitrogen.

Effectiveness of initiatives to build resilience against climate change

Taillandier et al. revealed that using agroforestry as a climate change adaptation and mitigation strategy has been successful in the Global South. Farmers who planted a combination of crops and trees/shrubs recorded lower insect/pest incidences, higher yields, and additional income from selling tree/shrub produce, boosting their resilience to climatic uncertainties (Taillandier et al.). A recent study by Mpala and Simatele evaluated the effectiveness of initiatives such as efficient use of water resources, use of early maturing crop varieties, and soil fertility management techniques in boosting crop yield and building the resilience of smallholder farmers in Zimbabwe against climate variability. The authors discovered that the identified climate-smart initiatives were successful and efficient in increasing the adopters' yield and income despite climate uncertainties. However, they admitted that the farmers require regular technical support to ensure the sustainability of the initial gains.

In India, Godara et al. reported that farmers who received regular information on climate-related issues (e.g., the onset of the rains, temperature, evapotranspiration, etc.) were more productive than those who did not. Using bio-economic models, Gbegbelegbe et al. simulated the impact of drought on yield and food security in southern Africa. The study found that food insecurity could worsen in the next years. Despite the drought, the authors reported that using stress-tolerant agricultural varieties, diversifying crops, and investing in water harvesting could boost productivity and food security. A related study by Amarnath et al. in Sri Lanka demonstrated that bundling climate-smart agricultural practices with weather index insurance could be effective in neutralizing the projected long-term severe yield declines and its income and food security implications.

Conclusion

Climate change remains a major threat to global food and nutrition security and attainment of the sustainable development goals. Based on the findings of the articles in this Research Topic, it can be concluded that members of farmer-based associations who receive regular extension services/education on climate change-related issues, and have access to credit or off-farm income-generating activities are more likely to adopt improved technologies/CSAs to build their resilience against the effect of climate change on their yield and income irrespective of the location. Generally, the existing climate-smart agricultural practices have been effective in building the resilience of vulnerable farmers against climate change. However, there is a need for awareness creation or promotion of climate-resilient crop varieties among the farmers to encourage adoption. The adopter of the existing initiatives should be provided with regular technical support to achieve the intended purpose.

Author contributions

SE: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. FA: Resources, Validation, Writing – review & editing. JO: Resources, Writing – review & editing. ZL: Writing – review & editing. JL: Writing – review & editing.

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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PGPR in Agriculture: A Sustainable Approach to Increasing Climate Change Resilience

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Growing environmental concerns are potentially narrowing global yield capacity of agricultural systems. Climate change is the most significant problem the world is currently facing. To meet global food demand, food production must be doubled by 2050; over exploitation of arable lands using unsustainable techniques might resolve food demand issues, but they have negative environmental effects. Current crop production systems are a major reason for changing global climate through diminishing biodiversity, physical and chemical soil degradation, and water pollution. The over application of fertilizers and pesticides contribute to climate change through greenhouse gas emissions (GHG) and toxic soil depositions. At this crucial time, there is a pressing need to transition to more sustainable crop production practices, ones that concentrate more on promoting sustainable mechanisms, which enable crops to grow well in resource limited and environmentally challenging environments, and also develop crops with greater resource use efficiency that have optimum sustainable yields across a wider array of environmental conditions. The phytomicrobiome is considered as one of the best strategies; a better alternative for sustainable agriculture, and a viable solution to meet the twin challenges of global food security and environmental stability. Use of the phytomicrobiome, due to its sustainable and environmentally friendly mechanisms of plant growth promotion, is becoming more widespread in the agricultural industry. Therefore, in this review, we emphasize the contribution of beneficial phytomicrobiome members, particularly plant growth promoting rhizobacteria (PGPR), as a strategy to sustainable improvement of plant growth and production in the face of climate change. Also, the roles of soil dwelling microbes in stress amelioration, nutrient supply (nitrogen fixation, phosphorus solubilization), and phytohormone production along with the factors that could potentially affect their efficiency have been discussed extensively. Lastly, limitations to expansion and use of biobased techniques, for instance, the perspective of crop producers, indigenous microbial competition and regulatory approval are discussed. This review largely focusses on the importance and need of sustainable and environmentally friendly approaches such as biobased/PGPR-based techniques in our agricultural systems, especially in the context of current climate change conditions, which are almost certain to worsen in near future.

Keywords: phytomicrobiome, PGPR, climate change, sustainability, abiotic stresses, phytohormones, biotic and abiotic stresses

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INTRODUCTION

To feed a dramatically growing world population, agricultural output must increase by 50% to sustain ∼9 billion people by 2050 (Alexandratos and Bruinsma, 2012). However, as the intensification of food production increases, the over-application of chemical fertilizers (Canfield et al., 2010) and the exploitation of arable land (Pastor et al., 2019) contribute further to greenhouse gas (GHG) emissions (Smith et al., 2013) and climate change (Richardson et al., 2012). The agricultural output response to climate change, setting aside any possible compensation due to increasing CO_2 levels, is 17% (Nelson et al., 2014). In addition to reducing crop productivity, climate change is also resulting in higher prices of agricultural products, increasing the risk of food insecurity for 77 million people by 2050 (Janssens et al., 2020). Climate change has caused significant yield losses to major cereal crops with about 3.8 and 5.5% yield reductions for maize and wheat, respectively (Lobell et al., 2011; Lipper et al., 2014). Climate change is rearing up, and with it, significant increases in global temperature, and occurrence of other abiotic stresses that are adversely affecting crop productivity. In such a situation, sustainable practices and the application of environmentally friendly technologies can help break this feedforward loop by improving resource use efficiency and increasing yield under a range of more extreme environmental conditions (Pareek et al., 2020), with the aim to improve healthy food production while reducing unsustainable inputs, thereby controlling extreme climatic conditions, and to improve soil health by sequestrating soil carbon, maintaining soil organic matter and inorganic nutrients (Drost et al., 2020). Some plants may grow reasonably well under more extreme growth conditions as they have evolved the plasticity to manage these variations. However, the productivity of most agricultural plants will decline, as more extreme environmental pressures will exceed their capacity to respond to stress. The rhizosphere, rhizoplane, and endosphere, the soil near the roots, the root surfaces, and the spaces between plant cells, respectively, are the plant-influenced areas with the greatest microbial diversity (Reinhold-Hurek et al., 2015); it affects plant growth and crop productivity, and has vital effects on carbon sequestration and the capacity for phytoremediation (Ojuederie and Babalola, 2017; Berlanas et al., 2019). Importantly, in the entire ecosystem, bacterial community composition is significantly co-related to soil properties; this is important as microbial abundance can mediate GHG emission (Ho et al., 2017). Moreover, the microbes living in rhizosphere contribute to efficient carbon cycling between the soil and the atmosphere and can reduce the loss of soil carbon through their metabolic activity (Bardgett et al., 2008). Host plants and soil properties, among other environmental conditions, have substantial influences on rhizosphere microbial diversity and abundance (Qiao et al., 2017). Importantly, it has been reported that a group of beneficial microbes, part of the phytomicrobiome, not only contribute to crop yield improvement but also enhance plant ability to resist biotic/abiotic stresses (Backer et al., 2018; Lyu et al., 2020). Beneficial phytomicrobiome members, including plant growth promotion rhizobacteria (PGPR), enhance plant growth by improving nutrient absorption, producing phytohormones, and releasing antibiotics to manage biotic stress (Lyu et al., 2020; Sindhu et al., 2020). The plant host and its associated phytomicrobiome are defined as the holobiont (Simon et al., 2019; Lyu et al., 2021); the unique opportunities that reside with plant-associated microbes have been recognized for several decades. More recently, the focus of this synergistic relationship has been shifting to the signal exchange aspect. Root exudates, including organic acids, sugar, vitamins, and other molecules, affect the abundance and behavior of plant-associated microbes (Huang et al., 2019). Reciprocally, the growth of host plants depend on microbe-to-plant signals (Ortíz-Castro et al., 2009). In this way, utilization of phytomicrobiomes (microbial inoculation, signal exogenous application) can be deployed to achieve the goal of establishing a more sustainable and resilient agricultural production system without additional chemical fertilization application.

This work aims to understand the microbe-microbe and plant-microbe interactions, including those mediated by signal exchange, and estimate the role of beneficial microbes, especially PGPR, as a sustainable approach to improving crop production. The need for development of a general formulation of this technology for global application against the challenges associated with climate change is also addressed.

PGPR—AN ALTERNATE APPROACH FOR SUSTAINABLE CROP PRODUCTION

The global food production gains in the 20th century after the green revolution was primarily based on two general areas of advance: chemical inputs (commercial fertilizers and pesticides) and genetic modifications through targeted breeding and gene manipulation. However, the continuous use of chemical fertilizers and pesticides, and their subsequent adverse effects on the environment have changed thinking around this. Scientists are approaching different techniques that could sustainably increase crop production including the utilization of phytomicrobiome members, which is now being recognized as a "fresh" green revolution (Lyu et al., 2020). The application of beneficial microbes on food crops has been studied extensively, however, their implementation in the field is very limited. The incorporation of phytomicrobiome members in agricultural systems as a sustainable approach for disease management and nutrient supplements could reduce the negative effects associated with the excess application of chemical inputs (fertilizers and pesticides) (Antar et al., 2021b). In addition, phytmicrobiome members have been employed as an effective strategy to mitigate certain biotic and abiotic stresses that could affect crop growth and production (Khan et al., 2020) (**Figure 1**).

Direct Mechanisms

Nutrient Acquisition

Nitrogen Fixation

Nitrogen (N) is one of the most important mineral nutrients for plants as it is an integral part of most of the plant physiological processes including photosynthesis and protein synthesis (Alori et al., 2017). Nitrogen, in the form of dinitrogen, makes up 79%

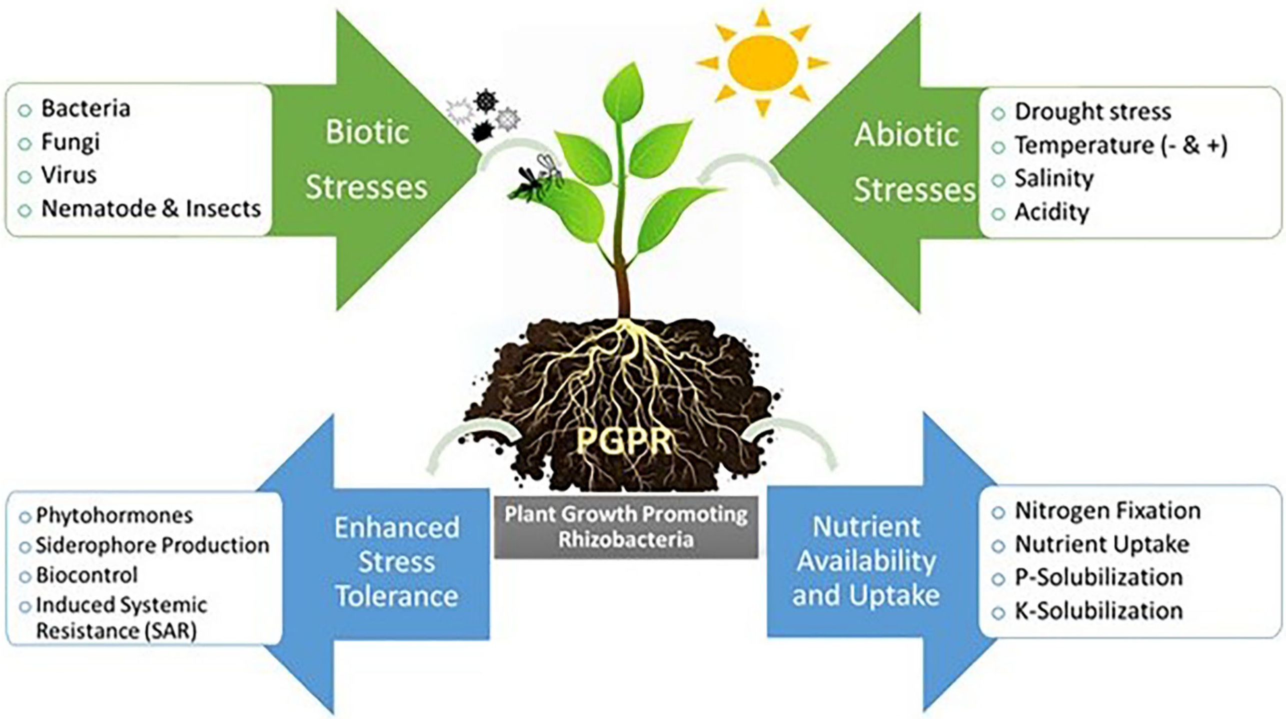

FIGURE 1 | Plant growth promoting rhizobacteria (PGPR) and plant interactions in rhizosphere.

of the earth's atmosphere, however, due to its triplet covalent bond, it has a very low level of reactivity, and can't be used directly by the plants. Nitrogen fertilizers, as the most efficient way of nitrogen supplement, have become a fundamental part of our crop production and agricultural systems, however, their continuous and ineffective excessive use is directly or indirectly contributing to the climate change by contaminating the environment through eutrophication, lethal emissions into the atmosphere or toxic deposition in ground water and other water bodies. It is estimated that only around 50% of added nitrogen is recovered by cropping systems (Bouchet et al., 2016), however, the remaining unavailable 50% stays in the soil as organic complexes (∼98% of the total soil nitrogen) or escapes through volatilization, leaching and runoff. Although, CO_2 is considered as the main culprit in climate change, nitrous oxide (N_2O); being 265 times more effective at heat trapping than CO_2 (Pep, 2019), is also a very important contributor. Therefore, alternatives should be considered that could sustainably increase nitrogen use efficiency (NUE) or at least reduce the fertilizer inputs for some extent. The members of phytomicrobiome, not all perhaps, have the capability to substantially reduce the need for soil nitrogen supplements either by fixing atmospheric nitrogen directly through legume-*rhizobium* interaction or indirectly, by assisting the nitrogen fixers through their secretions (Naamala and Smith, 2020). Nitrogen fixers are basically categorized into two major groups; the symbionts and the free-living nitrogen fixers, solely based on their type of association developed with plants. The symbiotic nitrogen fixers which include genera such as: *Rhizobium, Sinorhizobium, Azoarcus, Mesorhizobium, Frankia, Allorhizobium, Bradyrhizobium, Burkholderia, Azorhizobium,* and some *Achromobacter* strains (Babalola, 2010; Pérez-Montaño et al., 2014; Turan et al., 2016). The more notable bacterial genera of free living nitrogen fixers are: *Azoarcus, Herbaspirillum., Gluconacetobacter, Azospirillum, and Azotobacter* (Vessey, 2003).

These microorganisms utilize a substantial amount of energy to reduce the atmospheric nitrogen into available forms. For each mole of nitrogen fixed, 16 moles of ATP are required, and this energy primarily comes from oxidizing the organic molecules. To obtain these energy rich molecules, the non-photosynthetic nitrogen fixers completely rely on other organisms, while, photoautotrophic microorganism use sugars, produced by photosynthesis. In addition to the associated and symbiotic nitrogen fixing microorganisms; the most dominant and extensively studied group of nitrogen-fixing PGPMs, obtain these compounds from their host in exchange for the nitrogen fixed (Wagner, 2011). Total N_2 fixation in the world is estimated to be ∼175 Tg, of which symbiotic nitrogen fixation in legumes counts for ∼80 Tg by fixing 20–200 kg N fixed ha^{-1} yr^{-1}, and the other near half is industrially fixed while producing N fertilizers (∼88 Tg) (Hillel, 2008). Symbiotic nitrogen fixation begins with the crosstalk between nitrogen-fixing bacteria (e.g., rhizobia) and the host plant (legume) in the form of signal compounds, which will eventually lead to the formation of specialized structures (root nodules) where atmospheric nitrogen is reduced into available forms (primarily NH_3) (Naamala et al., 2016). More than 70 % of legumes develop symbiotic relationships with rhizobia, and fix up to 200 Kg N ha^{-1}. Legumes usually don't require nitrogen supplements, as they don't respond to fertilizers as long as they are capable of fixing atmospheric nitrogen, through symbiotic relationships with microbes, except for extensive application of N-fertilizers, which cause them reduce or completely shut down their nitrogen fixation because exploitation of the supplied fertilizer requires less energy than fixation of N_2 from the atmosphere. In addition to legumes, several studies of PGPRs have demonstrated that their application can reduce required application rates of chemical fertilizers to non-legumes. For example, PGPR inoculants on tomato coupled with application of 75% of the recommended N fertilizer rate, resulted in similar plant growth, yield and nutrient uptake, as compared to recommended fertilizer rate without PGPR inoculation, allowing a 25% reduction in chemical fertilizer supplementation. In addition, the co-inoculation of PGPR with AMF reduced the fertilizer input by 30% without any reduction in plant growth or yield (Adesemoye et al., 2009). Similarly, PGPR application with 80% of the recommended rates of nitrogen and phosphorus increased maize yield and biomass production by 11.7 and 17.9%, respectively, indicating a 20% reduction in fertilizer nitrogen and phosphorus input without hampering the growth and production of maize (Sood et al., 2018).

Phosphorus Solubilization

Phosphorus (P) is the second most highly required macronutrient required by plants, after nitrogen (Azziz et al., 2012; Tak et al., 2012). The total phosphorus content in soil has been reported to be in between 0.05 and 0.06%, but only 0.1% of that is available to plants because of its poor solubility, and its affinity with the soil matrix and organic complexes. Traditionally, to address phosphorus deficiencies, phosphorus-based fertilizers have been effectively adopted to recharge soil phosphorus, which is immediately available to plants. However, phosphorus supplementation through commercial fertilizers is an expensive approach, and the phosphorus often becomes unavailable to plants as it can readily be lost from the soil, and then can mix into local waterways and contaminate terrestrial and aquatic environments (Adesemoye and Kloepper, 2009).

Many beneficial microorganisms, including bacteria and fungi living in the soil, and those associated with plant roots are capable of solubilizing otherwise insoluble soil phosphorus (Bechtaoui et al., 2020). Phosphorus solubilizing bacteria (PSB) has been reported to reduce required P dosage by 25% (Sundara et al., 2002), and its influence increases when co-inoculated with other PGPR or AMF, as suggested by a 50% reduction in P supplementation (Khan et al., 2009). The principal mechanism followed by almost all phosphorus solubilizing microbes is to produce metabolites, mostly organic acids, in the form of gluconic and keto gluconic acids, which through their hydroxyl and carboxyl groups chelate the cations bound to phosphate (Bates and Lynch, 2001; Vassilev et al., 2006; Heydari et al., 2007), thereby solubilize the insoluble phosphorus into the soil solution, and make it accessible for plant uptake (Riaz et al., 2021). There is an array of phosphorus solubilizing bacteria that are capable of mobilizing forms of phosphorus, which are poorly accessible. These taxa include *Bacillus circulans*, *Agrobacterium spp*, *Pseudomonas spp* (Babalola and Glick, 2012), *Bacillus* (Raj et al., 2014), *Rhizobium* (Tajini et al., 2012), *Paenibacillus* (Bidondo et al., 2011), *Burkholderia* (Istina et al., 2015), *Azotobacter* (Kumar et al., 2014), *Enterobacter*, and *Erwinia* (Chakraborty et al., 2009). Similarly, the most efficient phosphate solubilizing fungi (PSF) are generally strains of *Alternaria, Achrothcium, Aspergillus, Cephalosporium, Arthrobotrys, Curvularia, Cladosporium, Rhizopus, Chaetomium, Cunninghamella, Glomus, Helminthosporium, Fusarium, Micromonospora, Mortierella, Myrothecium, Penicillium, Phoma, Pythium, Pichia fermentans, Populospora, Rhizoctonia, Trichoderma,* and many others (Srinivasan et al., 2012; Sharma et al., 2013).

Potassium Solubilization

Many microorganisms, especially fungal and bacterial species, are involved in mutual intimate relationships with plants and are able to solubilize potassium (K) in the soil (Gundala et al., 2013; Setiawati and Mutmainnah, 2016). The first study on potassium solubilization (Muentz, 1890) demonstrated the role of microorganisms in solubilizing potassium bearing rocks. A broad range of K-solubilizing microbes including, *Bacillus edaphicus* (Sheng and He, 2006), *Bacillus megaterium, Arthrobacter sp.* (Keshavarz Zarjani et al., 2013), *and Paenibacillus glucanolyticus* (Sangeeth et al., 2012) have been shown to release potassium from insoluble and fixed forms of K minerals by degrading silicate minerals. Studies carried out on the effects of plant growth promoting microbes (PGPM) on plant growth promotion revealed that the growth promotion was linked to increased potassium availability, related to secretion of organic acids by the K-solubilizing microorganisms (Badr et al., 2006; Sheng and He, 2006). Organic acids such as oxalate, citrate, acetate, ferulic acid and coumaric acid produced by microorganisms present in the soil increases the mineral dissolution rate and production of protons through acidification of the soil rhizosphere leading to the solubilization of mineral K (Prajapati and Modi, 2012; Setiawati and Mutmainnah, 2016). Thus, in order to achieve biological development for sustainable agriculture, researchers concluded that, the use of PGPM such as potassium solubilizing bacteria (PSB) can be a reliable biofertilizer, enhancing plant nutrient availability and so allowing reduced use of chemical fertilizers (Vessey, 2003; Archana et al., 2012; Prajapati et al., 2013).

Siderophore Production

Iron is a vital element for plants and other photosynthetic organisms since it plays a pivotal role as an enzymatic cofactor for various metabolic processes such as photosynthesis, amino acid synthesis, respiration, nitrogen fixation, and oxygen transport. Iron is one of the most abundant elements in the earth's crust; commonly exists in two oxidation states: Fe^{2+} and Fe^{3+}; the later of which is much less accessible to the plants due to its formation of insoluble iron oxides/hydroxides (Zuo and Zhang, 2011). Studies have revealed that some plant growth promoting bacteria (PGPB) sequester iron from the soil by releasing low molecular weight compounds (400–1,500 Da). Such iron-chelating compounds, siderophores, are able to bind ferric ions and ultimately make iron readily available for uptake by plant cells (Dalcorso et al., 2013; Saha et al., 2013; Goswami et al., 2016). In addition, siderophores secreted by PGPB have a much higher affinity to sequester iron than those produced by fungi or the plant itself (Saha et al., 2016).

Many microorganisms have been isolated and screened to evaluate their ability to produce siderophores, from both marine and terrestrial ecosystems (Sandy and Butler, 2009; Rezanka et al., 2018). Over 500 terrestrial and marine siderophores, with different chemical structures, have been identified so far (Chu et al., 2010; Hider and Kong, 2010). These are classified into four main groups: phenolates, hydroxamates, pyoverdines and carboxylates (Daly et al., 2017). More than 90% of siderophore-producing bacterial isolates belong to the gram-negative bacteria; *Enterobacter* and *Pseudomonas* dominate; few gram-positive genera such as *Bacillus* and *Rhodococcus* are able to produce siderophores - <2% of the total (Tian et al., 2009). From a bioprospecting perspective, studies suggest that most rhizobacteria, screened either from soil or plant root tissues, have the capability to enhance plant growth through siderophore production if inoculated into iron deficient soils (Tian et al., 2009). Production of siderophores by beneficial soil/plant associated microbes is also an important mechanism in terms of biological control, by outcompeting plant pathogens for iron sources, resulting in restriction of iron availability to these deleterious plant pathogens (Shanmugaiah et al., 2015).

Zinc Solubilization

Zinc (Zn) is an essential plant micronutrient, crucial for plant growth and development, required in very minute concentrations ranging from 5 to 100 mg kg^{-1} (Goteti et al., 2013). Zn plays a pivotal role in plant growth as it is an essential component of key plant physiological processes including chlorophyl formation, and activation enzymes involved in auxin and carbohydrate metabolism, synthesis of proteins, lipids and nucleic acids (Krämer and Clemens, 2005), and in the context of developing climate scenarios, it helps the plants withstand more extreme environmental conditions, including drought and extremes of temperature (Umair Hassan et al., 2020). However, zinc in most of agricultural soils is either deficient or exists in fixed forms in the soil, making it unavailable to plants (Sadeghzadeh, 2013). As reported by the Food and Agricultural Organization (FAO), more than 50% of the soils around the world are zinc deficient (FAO, 2002), mainly due to Zn association with naturally occurring mineral forms such as zincite (ZnO), sphalerite (ZnFe), smithsonite (ZnCO3), zinc silicates (ZnSiO3), willemite (ZnSiO4), and zinc sulfide (ZnS) (Saravanan et al., 2011) which are generally unavailable for plant uptake.

One way to alleviate Zn deficiency is the application of inorganic fertilizers, although this comes with a degree of environmental damage and, as indicated, much of it becomes unavailable to plants. Perhaps a better strategy for overcoming this problem is using plant growth promoting rhizobacteria (PGPR), which are known for their role in solubilizing naturally occurring cation bearing minerals. PGPR, have been shown to solubilize unavailable forms of zinc through chelation, exchange reaction mechanisms, acidification and dissolution processes by secreting organic acids into the soil (Hussain et al., 2015). Subramanian et al. (2009) reported both bacteria and fungi to increase Zn nutrient availability in the rhizosphere by solubilizing the unavailable forms of zinc. A number of studies clearly demonstrate that inoculation of Zn mobilizing PGPR significantly increase yield of cereal crops including, but not limited to, maize (Goteti et al., 2013), wheat (Kutman et al., 2010; Ullah et al., 2015; Kamran et al., 2017), and rice (Tariq et al., 2007; Vaid et al., 2014).

As global food demand rises, due to increasing requirements for staple crops to feed the dramatically growing population, an increasing demand for pesticides and synthetic fertilizers is required to increase crop productivity, but this has the potential to lead to serious environmental problems. Although, we may not be able to substitute mineral fertilizers with biofertilizers at this time, we at least assure a significant reduction in chemical and unsustainable inputs by incorporating beneficial microbes into agricultural production, thereby contributing to climate change mitigation.

Phytohormone Production by PGPR and Plant Health

Root-associated microbes including symbiotic or endophytic bacteria play a huge role in the production of plant growth hormones (phytohormones) which influence seed germination, development of root systems for better nutrient uptake, development/elaboration of vascular tissue, shoot elongation, flowering and overall plant growth (Sgroy et al., 2009; Antar et al., 2021a). Several studies indicate the potential of enhanced plant stress tolerance and growth promotion through hormones. These include abscisic acid in corn (Sgroy et al., 2009), cytokinins in wheat (Kudoyarova et al., 2014), auxin in rice and Lavandula dentate (Pereira et al., 2016; Etesami and Beattie, 2017) and gibberellins in cucumber, tomato, young radish and rice (Kang et al., 2014). In plants, hormone levels can be modulated through microbe-produced plant growth regulators, which exert effects close to those of exogenous plant phytohormonal applications (Egamberdieva, 2009; Turan et al., 2014). Microbe-produced phytohormones such as auxins and cytokinins resemble plant-synthesized phytohormones and regulate plant hormone levels influencing photosynthetic processes to promote plant growth and development, and activates defense responses to pathogens (Backer et al., 2018).

Auxins are an important group of hormones for plant growth and development. Indole Acetic Acid (IAA) is the most commonly found and physiologically active phytohormone in plants, active in upregulating and downregulating gene expression. Shoot apical meristems of plants produce IAA in the form of free/diffusible auxins and can be found in almost all plant tissues (Maheshwari et al., 2015). It has been reported that more than 80% of rhizospheric bacteria are able to synthesize and release auxins. IAA production, which is common among rhizospheric bacteria, involves several biosynthesis pathways, and is carried out by a range of bacterial genera including

Aeromonas, Azotbacter, Bacillus, Bradyrhizobium, Burkholderia, Enterobacter, Mesorhizobium, Pseudomonas, Rhizobium, and *Sinorhizobium* (Ahmad et al., 2008; Celloto et al., 2012; Sharma et al., 2016; Cakmakci et al., 2020). In some cases, a single bacterial strain produces IAA using more than one pathway. These biosynthesis pathways can be independent of, or dependent on, tryptophan, an important precursor molecule for IAA (Kashyap et al., 2019), with pathways sourcing from decomposed roots or exudates from bacterial cells (Spaepen et al., 2007; Egamberdieva et al., 2017).

The ability of rhizospheric beneficial bacteria to synthesize IAA under salinity stress conditions could play a crucial role in balancing and regulating IAA levels in the roots, leading to improved plant responses to salinity stress (Egamberdieva et al., 2015). It has recently been reported that microbe-produced IAA can enhance root and shoot biomass production under water deficit conditions (Kumar et al., 2019). In addition to IAA, various physiological processes regulating plant growth and development can be controlled through many PGPR-synthesized phytohormones such as indole lactic acid (ILA), indole-3-butyric acid (IBA), indole-3-propionic acid (IPA), indole-3-pyruvic acid (IPA), 2,4-dichlorophenoxy acetic acid (2,4-D) and 2-methyl-4-chlorophenoxy acetic acid (MCPA) and tryptophol (TOL) (Ijaz et al., 2019; Swarnalakshmi et al., 2020).

Cytokinins are another group of hormones influencing plant growth and development by regulating physiological processes involved in seed germination, cell division, apical dominance, root and shoot growth, flower and fruit production, leaf senescence, interactions of plants with pathogens, nutrient mobilization and assimilation (Egamberdieva et al., 2015; Akhtar et al., 2020). It has been reported that cytokinin alone or through its interactions other phytohormones, such as auxin and abscisic acid, could promote the growth of salt stressed plants, enhancing tolerance by altering gene expression (Kang et al., 2012; Kunikowska et al., 2013). Like auxins, PGPR such as *Arthrobacter, Bacillus, Azospirillum* and *Pseudomonas* have been reported to synthesize cytokinins, causing their positive impacts on root system. Cytokinin producing PGPR are not only important for promoting plant growth and development, but are effective biocontrol agents against various pathogens as well (Naz et al., 2009; Maheshwari et al., 2015). It is well-documented that plants and plant-associated microorganisms contain more than 30 growth-promoting cytokinin compounds released at various concentrations (Hayat et al., 2012; Amara et al., 2015).

In the past two decades, several studies have reported the effects of cytokinin producing PGPR on root system architecture, plant growth and tolerance to biotic and abiotic stresses including drought (Arkhipova et al., 2007; Dodd et al., 2010; Egamberdieva et al., 2015), salinity (Naz et al., 2009; Zhou et al., 2017; Cordero et al., 2018), bacterial pathogens (Naseem et al., 2014; Grosskinsky et al., 2016; Spallek et al., 2018; Dermastia, 2019), fungal pathogens (Mishra et al., 2018; Spallek et al., 2018; Vrabka et al., 2019) and insect pests (Giron and Glevarec, 2014; Brutting et al., 2018; Zhang et al., 2018).

Indirect Mechanisms

PGPR Derived Crop Tolerance Against Abiotic Stresses

As the climate change conditions continue to develop, more extreme environmental conditions are becoming more frequent, for example, drought, salinity, high and low temperatures, heavy metal toxicity, and nutrient deficiency, which can cause extensive annually reductions in overall crop production, yield and quality worldwide (Acquaah, 2009; Awasthi et al., 2014; Shrivastava and Kumar, 2015; Mishra et al., 2017). Climate change has aggravated the frequency and intensity of abiotic stresses, specifically drought and high temperature, causing remarkable losses in principal cereal species such as wheat, maize, and barely (Lobell and Field, 2007; Vogel et al., 2019). A recent heat wave and drought resulted in a reduced crop yield which caused a lack of fodder across the European countries (Mazumdaru, 2018). A co-occurrence of different abiotic stresses affecting crops in field environments is unfavorable for plant growth, development, and production (Mittler, 2006). High levels of soil salinity and drought, and their subsequent secondary effects including osmotic, oxidative and ionic stress, are considered to be major hindrances of agriculture output (Kaushal and Wani, 2016). When plants encounter stressful conditions, internal metabolism is disrupted by metabolic enzyme inhibition, substrate scarcity, excess demand for various compounds, or a combination of these factors. Hence, metabolic reconfiguration is obligatory to meet the requirements for anti-stress agents including compatible solutes, antioxidants, and proteins to resist unfavorable conditions (Obata and Fernie, 2012). Advances in molecular studies have identified signal transduction pathways and characteristics of underlying plant stress responses mechanisms, highlighting several physical, biochemical, and physiological changes by each stress elicitors. Implementing a sustainable strategy to improve plant resistance against such environmental limitations is of great importance to secure and optimize global food production. One of the eco-friendly approaches is the application of PGPR and/or their byproducts (Mayak et al., 2004; Bano and Fatima, 2009; Piccoli and Bottini, 2013; Zafar-Ul-Hye et al., 2014; Qin et al., 2016; Abd El-Daim et al., 2019; Ipek et al., 2019), which can sustainably assist the plants to withstand the extreme environmental conditions (**Table 1**).

PGPR mediated plant osmolytes homeostasis results from accumulation of specific solutes, including proline, sugars, polyamines, betaines, polyhydric alcohols, and other amino acids, and plays a major role in retaining turgor-driven cellular swelling to withstand osmotic stress resulting from drought and high levels of soil salinity (Vurukonda et al., 2016). PGPR discharge osmolytes, which work in combination with those produced by plants, to synergistically maintain plant health by improving plant growth and development (Sandhya et al., 2010; Vardharajula et al., 2011). Inoculation of maize with three PGPR strains caused increased choline and glycine betaine accumulation and leaf relative water content, resulting in plant resistance and growth under drought conditions (Gou et al.,

TABLE 1 | Crop abiotic stress amelioration by PGPR.

Stress type	PGPR	Crop	Mode of action	References
Salinity	*Paenibacillus mucilaginosus*	Soybean (*Glycine max*)	Volatile organic compounds produced by bacteria reduced Na^{+} ions in root and shoot and increased proline content in root	Ma et al., 2018
Drought and salinity	*Arthrobacter protophormiae* (SA3) and *Dietzia natronolimnaea* (STR1)	Wheat (*Triticum aestivum L.*)	Increasing IAA, reducing ABA and ACC level, adjusting expression of ethylene signaling regulatory compartment (CTR1) pathway and DREB2 transcription factor	Barnawal et al., 2017
Drought	*Klebsiella variicola F2* (KJ465989) *Raoultella planticola YL2* (KJ465991) *Pseudomonas fluorescens* YX2	Maize (*Zea mays*)	Induced accumulation of glycinebetaine and choline led to decline in water loss	Gou et al., 2015
Drought	The single inoculant of RAA3 (*Variovorax paradoxus*) and a consortium inoculant of four bacteria *Pseudomonas palleroniana*, (*Pseudomonas fluorescens*, *Pseudomonas palleroniana)*	Finger millet (*Eleusine coracana*)	Producing ACC deaminase and increased ROS assisted in drought stress toleration	Chandra et al., 2020
Drought and heavy metals	*Rhizobium leguminosarum* bv. *viciae*	Pea (*Pisum sativum* L.)	ACC deaminase increased nodulation, shoot biomass, water use efficiency and nutrient uptake	Belimov et al., 2019
Drought stress	*Pseudomonas azotoformans* FAP5	Wheat (*Triticum asetivum*)	Biofilm development improved morphological and physiological attributes	Ansari et al., 2021
High temperature	*Bacillus safensis (NCBI JX660689) and Ochrobactrum pseudogrignonens (NCBI JX660688)*	Wheat (*Triticum aestivum L.*)	Enhanced antioxidant signaling and reduced chloroplast and membrane injury	Sarkar et al., 2018

TABLE 2 | PGPR derived crop biotic stress tolerance.

PGPM	Biotic stress	Crops	References
Pseudomonas putida and *Rothia* sp	*Spodoptera litura*	*Solanum lycopersicum*	Bano and Muqarab, 2017
Bacillus amyloliquefaciens (SN13)	*Rhizoctonia solani*	*Oryza sativa*	Srivastava et al., 2016
Rhizobium etli strain G12	*Aphis gossypii* Glover	*Cucurbita pepo*	Martinuz et al., 2012
Peanibacillus lentimorbus B-30488	cucumber mosaic virus	Nicotiana tabacum cv White burley	Kumar et al., 2016
Pseudomonas sp. 23S	Clavibacter michiganensis	*Solanum lycopersicum* L	Takishita et al., 2018
Tricoderma koningiopsis Th003 WP	*Fusarium oxysporum*	*Physalis peruviana*	Díaz et al., 2013
Pseudomonas chlororaphis R47	*Phytophthora infestans*	*Solanum tuberosum*	Dixit et al., 2016
Bradyrhizobium japonicum NCIM 2746	*Rhizopus sp*. and, *Fusarium sp*	*Glycine max* L	Khandelwal et al., 2002
Pseudomonas fluorescens	*Pythium ultimum*	*Gossypium* sp	Hassen et al., 2016
Pseudomonas aeruginosa 7NSK2	*Pythium splendens*	*Lycopersicon esculentum*	Buysens et al., 1996
Serratia plymuthica strain C-1, *Chromobacterium sp*. strain C-61 and *Lysobacter enzymogenes* strain C-3 consortium	*Phytophthora capsici*	*Cupsicum spp*	Kim et al., 2008
Pseudomonas fluorescens	*Fusarium graminearum*	*Triticum aestivum* (wheat) cv. Tabuki	Moussa et al., 2013
Bacillus amyloliquefaciens LY-1	*Peronophythora litchii*	Litchi (*Litchi chinensis* Sonn.)	Wu et al., 2017
Corynebacterium agropyri (UPMP7)	*Pyricularia oryzae*	*Oryza sativa*	Ng et al., 2016
Bacillus licheniformis	sunflower necrosis virus disease	Sunflower	Srinivasan and Mathivanan, 2011
Streptomyces thermocarboxydus	*Fusarium* wilt	*Solanum lycopersicum* L	Passari et al., 2019
Rhizobium leguminosarum	Bean yellow mosaic virus (BYMV)	*Vicia faba*	Al-Ani and Adhab, 2013

2015). In another study, application of a combination of PGPR, compost, and mineral fertilizer caused higher levels of soluble sugar and proline content, which enhanced the ability to maintain membrane stability, chlorophyll content, and water potential in wheat during stressful conditions (Kanwal et al., 2017). Likewise, higher plant tolerance to water scarcity reported in cultivars of rice inoculated with PGPR consortia was associated with the accumulation of proline (Gusain et al., 2015).

PGPR Derived Crop Biotic Stress Tolerance

Biotic stresses, such as pests and diseases, are a common problem in agricultural production and results in significant crop loss. Increases in global temperature and changes in precipitation, in some parts of the world, due to climate change, has led to new crop pests and diseases (Naamala and Smith, 2020). Tools such as biotechnology and plant breeding have been used to address these pressures. Although successful outcomes have been observed, plant breeding is a long process and developed cultivars may succumb to new pests and diseases. PGPM can act as biocontrol agents for plant protection against various pathogens including fungi, bacteria, viruses and insects (Mishra et al., 2015; Myresiotis et al., 2015; Ali et al., 2020). They have several advantages compared to chemical pesticides, including being safe for humans and the environment, degrading more easily in soil and having lower potential to result in the development of resistance in the pathogens (Berg and Smalla, 2009). Previous literature has indicated the potential for disease reduction in major crops, such as rice, wheat, and corn by using seeds treated with microbial biocontrol agents (Heydari et al., 2007; Karthiba et al., 2010; Senthilraja et al., 2013). PGPM are a hopeful approach that can complement or supplement existing integrated biotic stress management practices, such as crop rotation, cautious and limited use of chemicals, as well as plant breeding and biotechnology. Research has shown a number of promising PGPM strains for use in pathogen biocontrol (**Table 2**), some of which have already been commercialized (Alizadeh et al., 2013; Moussa et al., 2013; De Vrieze et al., 2018; Zhao et al., 2018), as single strains or as a consortium. For instance, *Trichoderma harzianum* Tr6, and *Pseudomonas* sp. Ps14, enhanced cucumber's resistance to *Fusarium oxysporum* f. sp. *radicis cucumerinum* through induced systemic resistance (ISR) (Alizadeh et al., 2013). *Pseudomonas fluorescens* and *Bacillus subtilis* were reported to reduce the negative effects of *Fusarium graminearum* on wheat (Moussa et al., 2013). *Bacillus cepacia* mitigated the effect of *Fusarium oxysporum* and *Fusarium culmorum* in potato under storage conditions (Recep et al., 2009). *Pseudomonas migulae* Pf014 and *Bacillus amyloliquefaciens* Bs006 were reported to mitigate the effects of *Fusarium oxysporum* in cape gooseberry (Díaz et al., 2013). *Bacillus* and species, such as *Bacillus subtilis* (Sneb 815), *Pseudomonas putida* (Sneb 821), and *Pseudomonas fluorescens* have been reported to affect the growth cycle of *Meloidogyne incognita* (Zhao et al., 2018; Viljoen et al., 2019). A consortium of *Fusarium oxysporum* Fo162 and *Rhizobium etli* induced systemic resistance to *Aphis gossypii* (Martinuz et al., 2012). *Bacillus subtilis* slowed the growth of *Bemisia tabaci* in tomato plants.

Consortia are believed to be more effective at controlling biotic stress (Alizadeh et al., 2013; Zhao et al., 2018) than single inoculants. Although this has been shown in some research, others have shown the contrary. Therefore, more research is needed to come to a sound conclusion. However, consortia have some advantages over single strains which may lead a better efficiency. For instance, microbial species may synergistically interact and confer benefits to each other (De Vrieze et al., 2018; Zhao et al., 2018). Such benefits may include production of secondary metabolites such as exopolysaccharides that might render the non-producing strain resistant to stress (Mehnaz, 2016), or the breakdown of substrates to forms that other members of the consortium can use (Bender et al., 2016). Perhaps this may explain why ineffective strains sometimes become effective in a consortium. For instance, in an experiment conducted by Santhanam et al. (2015), two bacterial strains with insignificant effects on reducing mortality in tobacco due to sudden wilt pathogens, became effective upon inclusion in a consortium with three other bacteria (Santhanam et al., 2015). However, some PGPM may be inefficient in a consortium but efficient as single strains (Zhao et al., 2018). In conclusion, it is not always true that PGPM in a consortium will perform better than single strain.

PGPM employ a number of mechanisms to mitigate biotic stress. They include direct mechanisms such as hyper parasitism and the production of substances such as antibiotics, which antagonize the pathogen (De Vrieze et al., 2018), as well as indirect mechanisms such as ISR (Alizadeh et al., 2013; Martínez-Medina et al., 2017; Romera et al., 2019) and competition for nutrients and niche space (Recep et al., 2009; Vanitha and Ramjegathesh, 2014; Tripathi et al., 2018). ISR enables the whole plant to develop more resistance to pathogens. ISR is largely a jasmonic acid and ethylene dependent pathway, that can function without the pathogenesis-related (*PR*) gene (Romera et al., 2019) although the signaling pathway may be PGPM and host plant species dependent (Alizadeh et al., 2013). It can be induced by transcription factor MYB72, hormones, and signal molecules such as auxins and nitric oxide (Zamioudis et al., 2015; Martínez-Medina et al., 2017; Romera et al., 2019). The process through which PGPM elicit ISR is not yet fully understood, although it is suggested that volatile organic compounds and microbe associated molecular patterns (MAMPS) are some of the major elicitors (Martínez-Medina et al., 2017; Tyagi et al., 2018).

Production of defense enzymes such as 1-aminocyclopropane1-carboxylate (ACC) deaminase has also been reported as a mechanism through which PGPM mitigate biotic stress (Toklikishvili et al., 2010; Dixit et al., 2016). PGPM may also attract natural enemies of the pathogen, thereby indirectly controlling the biotic stress (Schausberger et al., 2012; Alizadeh et al., 2013; Pangesti et al., 2015). There are also incidences where a biocontrol agent did not have a significant effect on the biotic stress response but increased crop yield in their presence. For instance, increased yield, in the presence of aphids was observed in bell pepper plants treated with *Bacillus subtilis* and *Bacillus amyloliquefaciens* (Herman et al., 2008). This may particularly be of interest in areas where the biotic stress has become unresponsive to other control and management options.

A PGPM may possess one or more mechanisms of biocontrol. For instance, species from genres *Bacillus, Pseudomonas, Alcaligenes, Rhizobium, Aeromonas, and Streptomyces* have been identified as biocontrol agents, and their ability to control plant pathogens have been well-documented (Ahmad et al., 2008; Alemu, 2016; Das et al., 2017; Zachow et al., 2017; Abdelmoteleb and González-Mendoza, 2020). These biocontrol agents produce biological compounds (secondary metabolites) that have broad spectrum effects, which may cause beneficial activity against plant pathogens. Among these, hydrogen cyanide (HCN) produced by many biocontrol agents has activity against a wide range of plant pathogens. HCN, sometimes referred to as prussic acid, is a volatile broad-spectrum secondary metabolite produced by many rhizobacteria; it plays a crucial role in biological control of many pathogenic bacteria in the soil. For example, the suppression of sunflower charcoal rot and tomato root knot diseases caused by *Macrophomina phaseolina* and *Meloidogyne javanica*, respectively, was attributed to the production of HCN secreted by bacterial strains (Siddiqui et al., 2006; Reetha et al., 2014). In addition, Vanitha and Ramjegathesh (2014) observed siderophore, antibiotic, and HCN production in *Pseudomonas fluorescens* species which affected proliferation of *Macrophomina phaseolina* (Tassi) Goid. Production of ACC- deaminase is believed to be the mechanism by which *Paenibacillus lentimorbus* B-30488 (B-30488) mitigates *Scelerotium rolfsii* in tomato (Dixit et al., 2016). Recent studies show that HCN may promote plant growth by hindering plant pathogens. The inhibition process starts in mitochondria where HCN disrupts electron transport to reduce energy supply to the cell, eventually leading to the death of pathogenic organisms.

Research in biocontrol is still on going and better strains will be discovered while existing ones may be improved. Use of microbial compounds either together with microbial cells or independently, is already a research area of interest. Such research may be able to solve some of the shortcomings associated with use of biocontrol technology, such as inconsistencies observed under field conditions. With some shortcomings of biocontrol addressed, the phytomicrobiome can be a good resource for mitigating biotic stress, particularly amidst the threat of climate change.

FACTORS LIMITING SOIL MICROBIAL STABILITY AND PERFORMANCE

As climate change conditions continue to develop, we anticipate more frequent occurrences of extreme environmental limitation, making life stressful for living beings including microbes. The role of the phytomicrobiome in promoting plant growth under optimal and/or challenging environmental conditions is considerable. The incorporation of phytomicrobiome members into agricultural systems is an important and sustainable climate change mitigation strategy. However, there are certain factors that could substantially limit microbial efficiency, particularly under field conditions. Existing studies on plants and their associations with phytomicrobiome members, have demonstrated one perspective regarding these relationships, for example, the plant (host) and a specific associated microbe have generally been the sole focus. We have rarely considered how this association is affected by other members of the phytomicrobiome community, and what other factors need to be considered before incorporating biological techniques into natural growth conditions. In this section, we discuss some of the major factors that could adversely affect PGPR efficiency predominantly when exposed to natural soil conditions (**Figure 2**).

Soil Temperature

Soil temperatures, as a consequence of developing climate change conditions, have gradually continued to rise (Zhang et al., 2019) making it increasingly difficult for living beings to survive, including those living in close association with the plants. Microbes, like all other forms of life, depend on optimum temperature for optimal proliferation, community diversity and physiological activities (Wu et al., 2010). Under extreme temperatures both plants and their associated microbial community suffer from extreme heat and cold stress (Khare and Arora, 2015; Zhang et al., 2020), which in turn, trigger physiological response mechanisms (Ma et al., 2018) in order to survive non-optimal temperatures. Perhaps, the variations in the temperature and its effects on PGPR-plant interactions may result in positive or negative outcomes. Soil warming significantly increases microbial respiration as well as mortality rate (Wu et al., 2010; Schindlbacher et al., 2011) resulting in potential ineffectiveness of PGPR. For instance, some rhizobia are able to produce nodules while tolerating heat stress (Gray and Smith, 2005), however, their efficiency might still be affected by high temperatures. High temperatures are also associated with reductions in plant root hairs. As a result, there is reduced surface area for plant microbe interactions in the soil.

Some PGPR thrive under low temperatures and their ability to enhance plant performance under cold temperatures is being more widely exploited (Pedranzani et al., 2016; Liu et al., 2017; Ghorbanpour et al., 2018) but the overall understanding of their potential and mechanisms is still incomplete, due to variations related to the plant species the PGPR were isolated from. Studies have shown that PGPR isolated from areas of high temperatures are best adapted to high temperatures (Gray and Smith, 2005) and vice versa. Sometimes microbes can persist at temperatures as high as 45°C (Ali et al., 2011) but functionality as PGPR may be lost as it may be expending much of its energy responding to the very challenging external environment. Similarly, at low temperatures metabolic activities of cells are reduced, leading to inhibition of normal activities as reported for *Bradyrhizobium japonicum* at 15°C (Antoun and Prévost, 2005). Furthermore, low rhizosphere temperatures have been reported to inhibit synthesis and release of plant-to-PGPR signaling compounds (Pan and Smith, 1998) which hinders effective engagement in the early stages of symbiotic associations. The fact that higher and lower temperatures have shown effects on the efficacy of PGPR (Dutta and Podile, 2010; Wu et al., 2010) suggests that temperature has substantial impact on gene expression by these microorganisms. This further cautions that PGPR should be evaluated for their suitability at specific soil temperatures, and

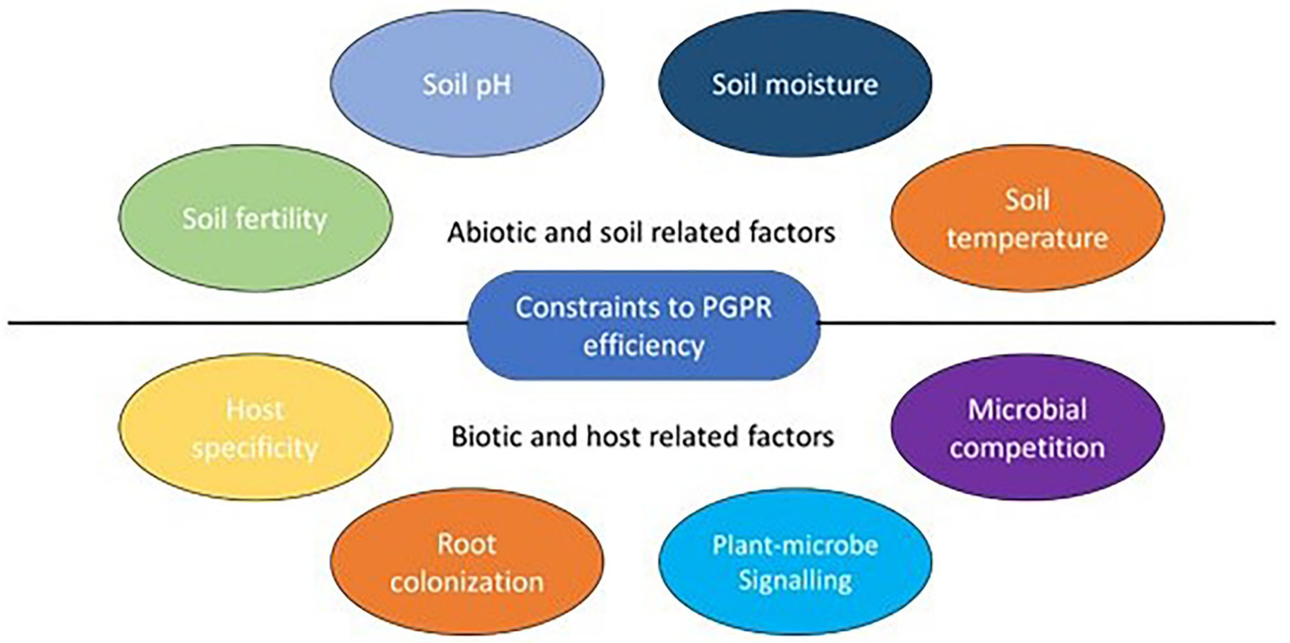

FIGURE 2 | Constraints to PGPR efficiency and stability.

probably other soil attributes, to achieve the intended results after application as climate change continues to increase global temperature fluctuation.

Varying Soil pH and PGPR Responses

In soil, the nutrient variability and availability to both plants and microbes is strongly affected by soil pH. pH is the measure of hydrogen cation concentration in the soil colloidal solution (Neina, 2019), which affects most chemical reactions in the soil. Microbial community and population dynamics have been shaped by pH variation in the soil. As a result, acidic soils are dominated by *Acidobacteria* (Shen et al., 2013), while *Actinobacteria* increasingly dominate in more alkaline soils (Jeanbille et al., 2016). The major effect of pH on the cell is the disruption of protein functioning (Hyyryläinen et al., 2001; Puissant et al., 2019). A very slight change in pH interferes with amino acid functional group ionization and impairs hydrogen bonding. This results in a change in protein folding leading to denaturation and cessation of enzymatic activities (Booth et al., 2002; Puissant et al., 2019).

Most rhizospheric microbes and plants share similar optimum pHs (near 6.0) for growth and survival. Environments with lower and higher pHs require microbes to adjust their biochemical properties; activities allowing adaptation to more extreme pH conditions may lead to altered microbial community structure (Roe et al., 1998). However, the relationship between these microbial survival mechanisms and plant growth promotion is not well-understood, and may result in positive or negative effects. Major functions of cells such as nutrient acquisition, cytoplasmic pH homeostasis, and protection of DNA and proteins are largely affected by low pH (Booth et al., 2002). Microorganisms can produce a thin biofilm composed of polysaccharides and proteins, which buffers the cell from changes in the pH (Wang et al., 2018), which may lead to reduced efficacy for PGPR.

Soil Fertility

Nutrient availability in the soil plays a major role in the maintenance of soil health and its productivity. Inherently less fertile soils tend to have smaller PGPR populations (Bhattarai et al., 2015) and the introduction of new microbes through soil inoculation results in poor microbial colonization of the area due to a lack of nutrients. Therefore, the efficacy of PGPR depends not only on less competition for resources (Ashman and Puri, 2013) and lower levels of antagonistic effects from other microbes, but also on the availability of nutrients in the soil; hence rapid rhizosphere colonization ultimately benefits the host plant. However, a higher diversity of microbial taxa in fertile soils results in a more complex inter- and intraspecies interactions which permit suppression antagonistic microbes. Furthermore, many studies of the legume-rhizobia symbiosis indicate that BNF efficiency tends to decrease in soils with high levels of soil N (Guinet et al., 2018; Romanyà and Casals, 2019). This emphasizes that sometimes scarcity of resources/stress creates more demand for the PGPR, to increase efficiency in assisting plants.

Host Specificity and Pre-association Signals

Plant-microbe interaction is, in many cases, dictated by host specificity, which limits broad spectrum application of PGPR across many plant species. In the soil, where diverse groups of microbes exist, a lack of specificity would result in higher competition among microbial taxa. Host plants—PGPR interactions, in many cases, are specific (Figueiredo et al., 2010), in part because their initial process of association involves signal cross talk between partners (Chagas et al., 2018). Signaling impacts PGPR efficacy in the soil in two main ways. Signaling between plants and microbes (Kan et al., 2017) is essential for the overall efficacy of many PGPR. Any alteration of the exudates produced by plant roots and signal molecules produced by microbes reduces the recognition of potential symbiotic partners. Factors such as rhizosphere temperature, soil pH, and fertility are all essential in plant and microbe growth and a deviation from optimal conditions may result in the production of altered root exudates and signaling compounds. Population related signal exchange within bacterial taxa is termed quorum sensing (QS) (Ryan et al., 2015; Smith et al., 2015; Kan et al., 2017; Chagas et al., 2018). QS shapes the behavior of the microbial populations by allowing or restricting interactions. N-acyl homoserine lactone (AHL) was the first QS identified from gram-negative bacteria (Eberhard et al., 1981). QS has a wide range of influences on microbe-to-microbe interactions such as initiating virulence and the production of antimicrobial compounds (Clinton and Rumbaugh, 2016; Chagas et al., 2018). Furthermore, QS is involved in plant-microbe interactions as well as microbe inter- and intraspecies communications, which all have the potential to affect plant growth and development (Clinton and Rumbaugh, 2016).

Most of this limited mutualistic association between plants and their PGPR reduces the possibility of plants benefiting from a wide range of microbes, which are either native, or new to a specific environment (Figueiredo et al., 2010; Wandrag et al., 2013). There is limited knowledge regarding promiscuity (ability to associate with a wide range of plant species) of PGPR, except for legume-rhizobia symbiosis (Keet et al., 2017). Promiscuous PGPR, such as some rhizobia, in most cases have shown inconsistent results in terms of efficacy (Labuschagne et al., 2010). Due to the specificity of interactions, it is not surprising to find that strains within the same species of PGPR can show differences in their effectiveness when interacting with the same host plant species (Dwivedi et al., 2015; Keet et al., 2017).

Soil Microbial Biodiversity; Hostility and Antagonism

There are many challenges associated with the introduction of specific PGPR into a new environment, such as competition and antagonistic effects of indigenous microbes (Clinton and Rumbaugh, 2016). In the soil, competition is high as the result of low nutrients and energy sources providing only about 5% of required nutrients when compared to simulated laboratory conditions (Ashman and Puri, 2013). Only meaningfully competitive microbes are able to survive during constant vying for nutrients, including carbon and nitrogen (Stengel and Gelin, 1998). Most studies hold the view that PGPR, to be ecologically competent, must be able to colonize the plant environment, while interacting harmoniously with indigenous microbes, to improve plant growth (Trivedi et al., 2012). Therefore, the efficiency of introduced PGPR meaningfully depends on the diversity of the indigenous population. The introduced PGPR may face antagonistic effects from the native soil microbes. This is a common defensive mechanism for most of microbes, against invasive microbes; some reports indicate that as much as 90% of *Actinomycete* sp. isolated from the rhizosphere show this behavior against *Bradyrhizobium japonicum* (Pugashetti et al., 1982). Moreover, soil microbes could alter root exudate characteristics leading to poor or no attraction of the inoculated PGPR, reducing rhizoshpere colonization (Gupta Sood, 2003).

PGPR-BASED PRODUCTS: AN ALTERNATIVE TO BYPASS FACTORS LIMITING PGPR EFFICIENCY

The effectiveness of beneficial microbes; successful association with the host and stability in the rhizosphere, is directly associated with varying environmental conditions and host related factors that could drastically affect microbial growth, stability and efficiency with regard to interactions with plants and other phytomicrobiome members. Considering the limitations and uncertainties associated with the use of microbial strains, alternate techniques that could bypass such limitations have been introduced which could improve plant health directly by stimulating plant growth or indirectly by helping other beneficial microbes. For instance, the use of microbial compounds and/or signals isolated from microbial cultures has shown promising effects on crop production with or without microbial strains under both stressed (drought and salinity) and unstressed environmental conditions (Nazari and Smith, 2020). These microbe-based compounds could be of different types with specific chemical distinctions. For instance, many of the known secreted microbial compounds are broad-spectrum non-ribosomal antibiotics, metabolic by-products, organic acids, lytic agents, and bacteriocins.

Growth stimulating compounds are usually excreted in response to externally generated stimuli, for instance, a signal received from the host plant, indicating nutrient deficiency or other suboptimal environmental conditions, and affecting microbial species in the rhizosphere (Nazari and Smith, 2020). However, the secretion of certain compounds does not necessarily require a specific environmental condition or an external stimulus. For instance, certain bacterial strains, when cultured in artificial media, produced compounds and/or signals that successfully promote plant growth, even in extreme environmental growth conditions. Perhaps such microbe-based compounds are able to provide benefit to a wider range of crop species as compared to microbial strains themselves, with the benefit of being unaffected by crop environmental conditions and without the specificities associated with microbes.

However, the isolation, identification and eventual commercialization of such compounds follow a very technical and complex procedure, which primarily begins by the isolation of plant associated "ecto" or endophytic microbes, respectively, from the rhizosphere and plant tissues, particularly from roots. This could be achieved through bioprospecting, the sampling of

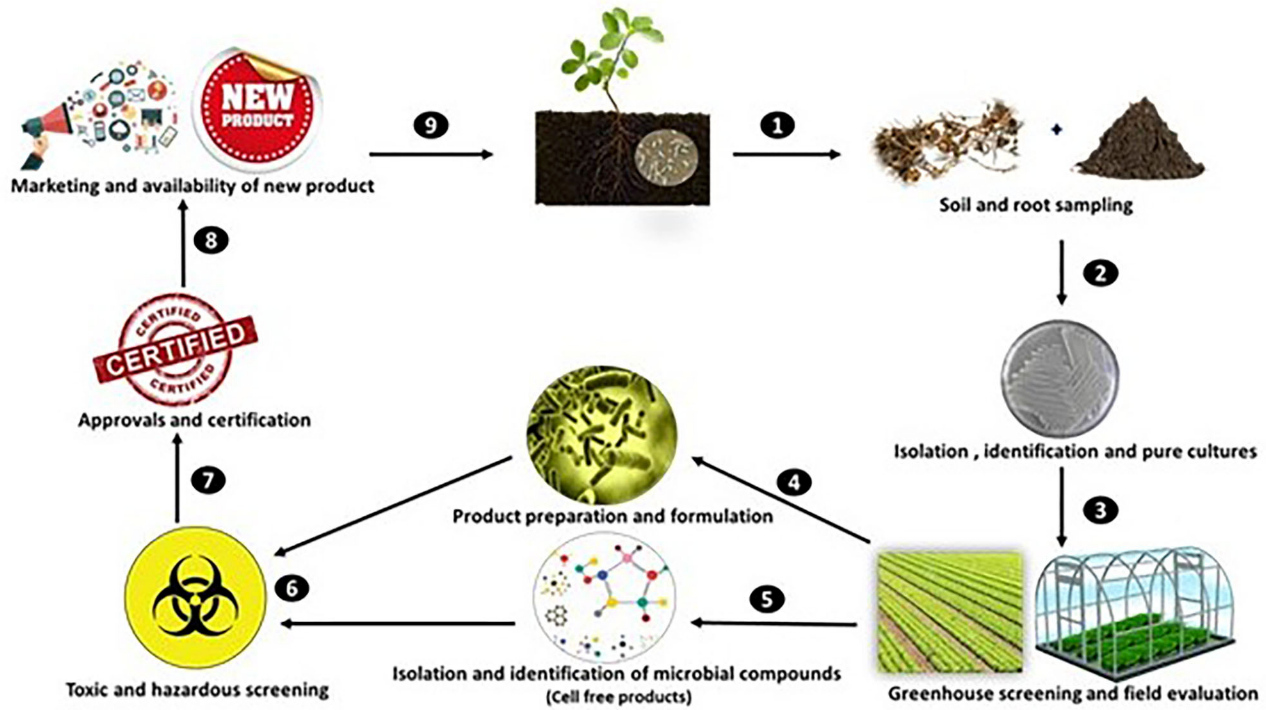

FIGURE 3 | Roadmap to the commercialization of biobased products.

plants or soil from a range of habitats, followed by immediate microbial isolation in the laboratory. Once rhizobacteria are isolated from the plant or soil, they can then be subjected to *in vitro* screening assays to assess their ability to enhance plant growth and their possible role as biocontrol agents against phytopathogens. Promising strains that show plant growth stimulation or antagonistic activities can then be screened under controlled environmental conditions during early plant growth, where eventually the effective strains are chosen and validated for further analysis under field conditions for their ability to enhance crop growth. After successful repetitive trials, most of the firms, after formulating the product, tend to commercialize biological strains as biofertilizers and/or biocontrol products, and so far, in North America more than 33 PGPR-based products have been registered for commercial use (Nakkeeran et al., 2005). The number of industries involved in commercial biological-based products has increased drastically in the 21st century, due to high demand for their application as a method of biocontrol and crop protection. However, considering the shelf life and unpredictable behavior of the desired biological strain, and most importantly the limiting factors discussed above, producers or distributors go a step ahead by isolating and identifying the growth stimulating compounds produced by growth promoting microbes. Thus, after successful field trials, the microbial strains are further cultured and screened for the growth stimulating compounds which includes isolation, identification and further experimentation on crops under various growth conditions. In order to commercialize these products or make it available for local users, these products have to go through an intensive vetting and registration processes established by the health or food security departments of concerned regions, following much the same pattern described above for microbial strains. After government approval the products can be commercialized and mad available to crop producers (**Figure 3**).

Potential Commercialized PGPR-Based Products

Thuricin 17

The bacteriocin thuricin 17, a subclass IId bacteriocin with a molecular weight of 3.162 kDa, is a single, small peptide isolated from a bacterium found in soybean root tissue which possesses inhibitory properties to related microbial strains. The bacterium was identified as *Bacillus thuringiensis* NEB17, an endophytic bacterium (Gray et al., 2006a,b). This kind of bacteriocin acts either as a microbe-microbe or a microbe-plant signaling molecule in the rhizosphere; it not only hampers competing microorganisms sharing its niche but also physically extends the niche by triggering plant growth, particularly when exposed to abiotic stress. These bacteriocins benefit the growth and development of important crops such as soybean, canola and corn (Lee et al., 2009; Schwinghamer et al., 2016a,b; Subramanian et al., 2016). Interestingly, thuricin 17 has no inhibitory effect against symbiotic nitrogen fixing rhizobia or other PGPR members (Gray and Smith, 2005). This signal molecule enhances plant growth through direct and indirect mechanisms (Nazari and Smith, 2020). Induction of resistance to disease (Mabood et al., 2014) and inhibition of pathogens are indirect mechanisms for plant growth stimulation. In direct stimulation, thuricin 17 binds to receptors in leaves or roots, acting as a stress signal, causing the enhancement of metabolic pathways such as increases in photosynthetic rates. It is well-established that plants raise photosynthetic rates under biotic stress to compensate for damaged tissues (Nowak and Caldwell, 1984). In this manner, thuricin 17 has activated stress responses without a real stress necessarily being present, resulting in an increase in net photosynthesis (Gray and Smith, 2005).

Lipochitooligosachrides

Lipochitoolicosaccharides are host specific signal compounds that are essential for establishing legume-rhizobia symbiotic associations. The signal exchange is crucial in facilitating the plant endophytic association with phytomicrobiome members. Before any physical contact, both partners begin this mutualistic interaction by exchanging signals. In legume-rhizobia association, isoflavonoids exuded from legume roots are perceived by rhizobia through a NodD (LysM-RLK) receptor, activating nod genes. However, distinct chemical signals are secreted in legume species, and only the correct rhizobia respond to that specific signal. In response to plant signals, rhizobia secret a combination of Nod factors (LCOs) and effector proteins, which are perceived by Nod factor-specific (LysM-RLK) receptors in plants (Shah and Smith, 2020). The receptor for the lipo-chitooligosaccharides is a LysM kinase for the legume-rhizobia symbioses; this receptor system seems to have initially evolved for pathogen detection almost 2 billion years ago (Gust et al., 2012; Carotenuto et al., 2017).

Lipo-chitooligosaccharides have been shown to increase plant growth for a wide range of plant species, including *Zea mays*, *Oryza sativa* (Poaceae), *Beta vulgaris* (Chenopodaceae), *Glycine max*, *Phaseolus vulgaris* (Fabaceae), and *Gossypium hirsutum* (Malvaceae) (Prithiviraj et al., 2003), particularly when plants are growing under stressful conditions (Subramanian and Smith, 2015; Zipfel and Oldroyd, 2017) including drought (Hu et al., 2013) and salinity. For instance, a proteomic study on salt stressed plants revealed that LCOs have a big impact on proteins involved in carbon and energy metabolic pathways indicating a promising and improved growth effect under salt stress (Subramanian et al., 2016). Signaling plays a crucial role in establishing successful associations but can be interrupted by specific environmental conditions, thus utilization of inoculants with LCO already present may compensate for the limiting effects of stressful conditions (e.g., drought), as determined by Cerezini et al. (2016).

CHALLENGES AND LIMITATIONS

With a growing need to sustainably increase crop productivity and counter the effects of climate change, the phytomicrobiome is a promising area of research (Kashyap et al., 2018). However, to be environmentally effective, the use of microbes and microbe-based compounds should be practiced on a larger scale. Despite conducting successful trials in laboratories and/or in controlled plant growth conditions, and having reasonable knowledge regarding microbial efficiency, we have not been overly successful in transferring these techniques to the field. In order to bridge this substantial gap, there is a need to understand the inconsistencies, uncertainties, issues and challenges following the use of microbes or microbe-based compounds in the field.

Farmers' Mindset

Since 1960, the agrochemicals (fertilizers and pesticides) and other farm technologies, which are the main underpinnings of the green revolution, have been the mainstay of agricultural production. The efficiency and immediate effect of chemical fertilizers and pesticides have developed a deep-rooted confidence among farmers and growers, making it difficult for novel techniques to be implemented and/or substituted (Moser et al., 2008). Undoubtedly, the contribution of these agro-inputs in increasing crop productivity is indispensable, however, the increasing GHG emissions from unsustainable agricultural practices has changed some of the thinking around this. So far, we haven't introduced any technologies that could totally substitute for fertilizers and other chemical inputs, however, sustainable techniques, for instance, organic fertilizes, humic substances, or bio-based products (microbes and microbe-based compounds) have been developed that could, to at least some extent, assist in combatting climate change by reducing the use of chemical inputs (fertilizers and pesticides). It may be challenging to transfer these techniques; particularly microbe-based products, to the field as it depends on farmers' mindsets and whether or not they are willing to take risks by implementing new strategies to their fields, especially those that may come with uncertainties.

The first thing that prevents farmers from adopting microbe-based techniques is the lack of practical evidence of their effectiveness in the field (Moser et al., 2008). It is certainly difficult for farmers to adopt technologies that lack the surety of being effective, or to give up more efficient techniques (pesticides and fertilizers) that have demonstrated efficacy for over 50 years. Secondly, in comparison to PGPR strains or PGPR related products, agro-chemicals in small doses have been found to be more effective and immediate in terms of nutrient availability and pathogen control, hence further limiting the likelihood of adopting PGPR and biobased products. Thirdly, high fixed costs of biofertilizers, biopesticides, and bio-compounds can pose a large disadvantage, driving potential adopters to rely on agro-chemicals. Since these products are new to the market, their prices will go down only when they are distributed and/or produced on a large scale.

In addition, considering the "cost to efficiency" ratios of bioproducts, chemical additives provide better efficiency at much lower costs. To tackle these issues and inconsistencies, more research should be done to raise awareness among growers and address their unique needs. We must develop economically viable products and provide practical evidence of the product's efficacy. In addition, there is an ultimate need to educate farmers regarding climate change, its consequences, and the role PGPM based products could play in mitigating climate change.

Crop Specificity of Microbes

One of the major challenges of using PGPMs is their unpredictable behavior in the field compared to under controlled environmental conditions. It is very difficult to predict an organism's reaction in natural environments even after conducting successful and effective trials in laboratories. One of the major reasons for this is plant-microbe specificity (Mushtaq, 2020). However, another challenge usually faced by PGPR developers is root colonization and viability of the desired inoculant. In order to populate an inoculant and to attain an effective response, the inoculant should colonize the host at a certain population density (Mcnear, 2013). However, the crop specificity of PGPR can be independent of root colonization. Beside crop specificity, environmental factors can strongly influence the viability and colonization of a PGPM strain, for instance soil type, temperature, moisture, and the presence of other competitive microbial entities in the rhizosphere. These vary from crop to crop and field to field (Saharan and Nehra, 2011), making it difficult and far more complex for the PGPR developers and commercial vendors to provide separate PGPR inoculants for different crops grown under different environmental conditions.

In order to address the inconsistencies associated with specificity, adaptability and colonization of single microbial inoculants, inoculants with two or more microbial species, or microbial consortia, constitute a potential approach (Naamala and Smith, 2020). While, microbial consortia have their own limitations, if well-formulated, they may be more promising than single strains by synergistically interacting with each other and/or helping other beneficial phytomicrobiome members in the rhizosphere. This may indirectly benefit host plants through the production of specific compounds that facilitate the colonization by other microbes, or might act as a signaling compound, further facilitating plant-microbe association (Bender et al., 2016). In addition, as the viability of PGPR strains varies among crop species and environmental conditions, microbial consortia consisting of two or more members from different genera or phyla with varying tolerance to environmental conditions have a better chance of survival and adaptability. However, it is very challenging to have compatible members in a consortium. It is reasonably probable that some of the members will produce compounds that are lethal to other members or may hinder their growth promoting capabilities (Jha and Saraf, 2015).

Considering the limitations and uncertainties associated with the use of microbial strains, microbial compounds and/or products are suggested to be suitable alternatives that could sustainably promote crop growth by successfully circumventing some of the critical environmental limitations, hindering microbial efficiency. For instance, the use of microbial compounds (e.g., thuricin 17 and lipo-chitooligosaccharides) has shown promising effects on crop production even under extreme environmental growth conditions (drought and salinity) (Nazari and Smith, 2020). Perhaps such microbe-based compounds will be able to provide benefit to a wider range of crop species as compared to microbial strains, with the benefit of being unaffected by crop environmental conditions and without the specificities associated with microbes. However, further molecular experiments are still required to better understand the metabolite-plant species-microbe combinations, and the time-course effect of host rhizosphere chemistry following the use of selective inoculants.

Legal and Regulatory Issues

One of the obstacles to the expansion and production of microbe-based products are risk assessment and testing policies set by every country, and sometimes subnational jurisdictions, to avoid the production and distribution of lethal/damaging organisms (Tabassum et al., 2017). Regulatory processes for biological or biobased products follow a very complex and extensive protocol set by the regulatory and health authorities of each country. The most intensive constraints for registering a biological or biobased product are the extensive time period, complex documentation and high fees associated with the whole process of product registration. Since, the registration and regulatory policies vary with country; as each country, or in some cases, each sub-jurisdiction has their own rules and norms to be addressed in order to register biobased products, and it can be very difficult for firms to meet the regulatory requirements, should they want to introduce their product in multiple regions or countries. Usually, a products registration requires a national approval with a certification provided by the Directorate General of Health or any other concerned regulatory authority. The product will then undergoes extensive and critical inspections and/or reviews by experts, supervised by the food safety authorities and national commissions of that particular country or region (Basu et al., 2021). Eventually, the firm will be notified with approvals and certification, which will allow the producers to commercialize their product under the strict policies and instructions of the certification authority. Climate change is a global issue, and sustainable techniques that could contribute to mitigating climate change should have simpler regulatory and registration policies. In addition, countries should be flexible or at least develop less complex policies for registering and transporting native and imported microbial technologies. Doing so might help firms or PGPR developers to feasibly expand and distribute PGPR-based techniques within and outside the country of origin.

CONCLUSIONS

The growing human population is causing demand of increased food production, but under conditions of intensifying climate change and a finite base of farmland. So far, chemical application (e.g., fertilization and pesticides) and molecular techniques (e.g., gene modification) have been used to address this challenge. As a more sustainable agricultural approach, PGPR that regularly establish mutualistic interactions with host plants related to nutrient absorption (N fixation, P and K solubilization and siderophore production), enhanced stress resistance (abiotic and biotic), regulation of plant development and physiology through signal compound production, including phytohormones and specific inter-organismal signal compounds. In a similar way, root exudates, secreted by host plants into the rhizosphere as a reduced carbon resource for phytomicrobiome members, help provide a stable habitat for microbe growth. Thus, the application of PGPR is an available and under-exploited mechanism to enhance yield and improve resilience of crop plants to the various conditions challenging crop growth, development and yield. However, environmental conditions, such as the soil temperature, pH and soil fertility do not just affect plant development, they also have influence on the efficiency of PGPR, which in turn alters the ability of cultivated plants to produce biomass and food materials under climate change related environmental extremes.

Because of the beneficial effects provided by beneficial phytomicrobiome members, their utilization and commercialization are now being much more widely considered. Potential products, such as the exogenous application of microbe-to-plant signal compounds (e.g., thuricin 17 and LCOs) already show positive effects on crop growth and development, and biomass and food production by key crops under specific abiotic stress conditions; often those associated with climate change. However, work still needs to be done to expand utilization of these products and potential products on a wider range crops, instead specific crop species. In addition, it is still unclear if the biodiversity of the plant-associated microbial community will be affected by the use of these products; at the same time the abundant community of soil microbes extant at the time PGPR technologies are applied can affect the growth of these added microbes and their ability to provide vital effects to the plant-microbe-soil ecosystem. Furthermore, < 1% of soil and plant-associated microbes can currently be cultured *in vitro* (Pham and Kim, 2012). Mutualistic and parasitic relationships between microbes and plants already exist, and have done so for several billion years; there is a considerable amount still to be learned about and exploited regarding these relationships.

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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Growing resilient futures: agroforestry as a pathway towards climate resilient development for smallholder farmers

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Climate change is increasing pressure on communities that are already experiencing high levels of vulnerability and poverty, threatening their subsistence. Among the most vulnerable are smallholder farmers in the Global South, who rely on their yields for food and income. Smallholders need to adapt to changes in rainfall, temperature, and weather patterns and their knock-on effects, and at the same time, ensure that their on-farm climate adaptations do not make climate change worse by increasing greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) emphasises the need for Climate Resilient Development Pathways (CRDPs) to support vulnerable communities, including smallholder farmers, in balancing climate adaptation, mitigation and development. CRDPs comprise reactive and/or preventive actions that key stakeholders (e.g., government, business, civil society and individuals, including smallholder farmers) can take to become more resilient in the context of a changing climate while not compromising their development or increasing emissions. The CRDP framework has so far remained conceptual, providing little information on how to actually create these pathways in practice. This paper addresses this gap, and with a focus on agroforestry projects and smallholders in the Global South, assesses how CRDPs can become more concrete and actionable through a focus on agroforestry: the voluntary combination of crop and/or pasture with trees and/or shrubs, considering its contribution to climate adaptation, mitigation and development. We draw on literature review and focus group data, analysed using Atlas.ti 23 and a coding process to present a tool relevant to project designers, policymakers and researchers to assess agroforestry projects according to different aspects of climate resilient development, with particular focus on smallholder farmers in the Global South. Evaluation of the tool found it is relevant and useful for project developers and funders to check that their projects follow the components of CRD, but the tool needs to be translated to the local context to better address local demands and reflect regional specificities, which focus group participants deemed possible.

KEYWORDS
sustainable agriculture, rural livelihoods, climate adaptation, climate mitigation, project development

1. Introduction

Temperatures have been rising globally, and extreme weather events have become more frequent and more devastating. These changes have emerged as a result of increased greenhouse gas (GHG) emissions, mostly linked to human activities, among which agriculture accounts for 25% of global emissions (Tubiello et al., 2022). As warming intensifies, more and more vulnerable communities will be further exposed to climate variabilities and extreme events (IPCC, 2022), increasing the risk of hunger, poverty and other development challenges. Such communities include smallholder farmers in the Global South, whose livelihoods directly depend on climate-sensitive natural resources.

Smallholder farmers represent c.70–80% of the world's farmers, producing 29% of global crops or 32% of world's food, on 24% of the available agricultural land (Ricciardi et al., 2018). The majority of smallholder farmers are currently located in the Global South, especially in Africa and Southeast-Asia (FAO, 2012). Two of the main characteristics of smallholder farmers is that they work on small plots of land (1–10 ha), with their direct family members, with whom they live on the land providing the farm labour (Chamberlin, 2008; Cousins, 2011). Due to their small plot sizes, smallholders often produce only enough to feed their family. Such subsistence farming means there is little opportunity for them to sell their products on the market or to a buyer to earn some money. Smallholders therefore commonly live on <$2 per person per day. Such low levels of income prevents them from meeting their basic social needs, investing in their farms, and shifting towards more sustainable farming practices under a changing climate.

Although economically deprived, smallholder farmers are not resource-less. They are often very well-connected to the land they cultivate and have practical knowledge and know-how about the specific conditions and practices for producing food on their land (e.g., local knowledge about which variety grows best, where and when to plant, when to harvest and so on, as well as farming practices such as traditional organic composting, crop rotation, or agroforestry; Singh and Singh, 2017). Local knowledge is nonetheless at risk of being lost. High numbers of the younger generation are leaving the family farm for cities, in the hope for a better future (Bisht et al., 2020), disrupting knowledge transmission. At worst, this could lead to a loss of local and indigenous knowledge, the successive abandonment of farms and an ensuing decrease in food production (de Scally and Doberstein, 2022). This is of particular concern considering that the world's population has recently exceeded 8 billion people, and is still increasing, all of whom need to eat (United Nations, 2022). Together, the issues of climate change, the precarious economic nature of smallholders, small plot sizes, and a growing human population, highlight the importance and urgency for transformation towards farming systems that can be climate resilient, addressing adaptation, mitigation, and development together, without exacerbating any of the pressures.

Agroforestry is one possible adaptation strategy that offers potential to open climate resilient development pathways. Agroforestry is an agricultural system involving the intentional mix of woody perennials (Somarriba, 1992), such as trees and shrubs, with crops and/or pasture (USDA, 2019) and has long been used in traditional smallholder systems. Agroforestry comes in different types (Brown et al., 2018; Lojka et al., 2022), of which the three most common are agrisilviculture (combining crops and trees), silvopastoralism (combining pasture and trees), and agro-silvo-pastoralism (combining crops and pasture with trees). Across the three types, agroforestry is characterised by the biological interaction between crops and trees (Somarriba, 1992) and can be customised and adapted to different and changing contexts with the use of different species. Gold et al. (2004) described agroforestry as a form of 'productive conservation'. While countries may perceive agroforestry as a tool to achieve nationally defined climate goals through carbon capture (Keur and Selin Norén, 2020; Waldén et al., 2020), it can also be viewed as a way to diversify production, leading to more diverse diets (Garrity et al., 2010) or enhanced profits with the sale of fruits. Evidence also suggests it can improve soil quality with the fixation of nutrients through the root network, with dead leaves and decomposing branches enriching the soil with biomass (Nyasimi et al., 2017). Trees in agroforestry may thus assume multiple functions:

- Economic functions: diversified crop production and associated increase in household income should crops be sold (Duffy et al., 2021), fodder (i.e., animal feed) reducing expenditure if it is grown on site (Brown et al., 2018).
- Social functions: time efficient on-farm firewood collection (Regmi, 2003), shade for animals/people (Meybeck et al., 2021), field boundary delimitation (Kalanzi et al., 2021).
- Environmental functions: windbreak for crops (Kalanzi et al., 2021), soil fertility and soil structural improvements, reduced erosion and improved water holding capacity (Franzel et al., 2014; Altieri et al., 2015; Nyasimi et al., 2017).

While agroforestry can help to reduce the impacts of more extreme climatic events (van Noordwijk et al., 2021), it also provides potential for mitigating climate change (Meybeck et al., 2021) with the capture of carbon (Salvini et al., 2016), while supporting development. Despite these benefits, agroforestry also presents challenges. The shift from monoculture to agroforestry involves major changes; one of which is investment in seedlings, plantlets, and small trees, requiring smallholder budgets to be adapted. Although often considered a low-level investment (Toensmeier, 2016; Ollinaho and Kröger, 2021), the initial outlay may, nonetheless, be a barrier to uptake. It also requires land to be taken out of production where the trees are planted which can have a negative impact on yields in the short term. In some regions, land tenure is not secure, but rather granted on a one-to-one basis. This can come as an extra barrier, especially when returns on investment are not immediately visible and take time. Farming practice change is also synonymous with knowledge acquisition and the learning of new skills, despite that different types of agroforestry have existed in traditional farming for centuries (Kansanga et al., 2021). A further drawback may be the competition between trees and crops, with one species impeding the development of another. As such, species need to be carefully chosen. Products from agroforestry may not have a market in the specific region or on a broader scale, limiting the potential for direct development and/or livelihood adaptation benefits. Finally, since agroforestry is tailorable to specific contexts (Mathez-Stiefel et al., 2016; Baker et al., 2023), it is not easily scalable. The form and the type of agroforestry may need to be re-assessed, and the tree species need to be adapted to context (Coe et al., 2014). Given its benefits, and despite its drawbacks, agroforestry is considered a potential climate resilient development pathway for smallholder farmers, even if benefits do emerge over different time frames (Chandra et al., 2017).

Many tools have been developed to assess agroforestry projects previously, but they take rather narrow approaches. The farm-level agroecology criteria tool (F-ACT; Colbert, 2019) is more extensive in its approach building on the three principles of sustainable food systems: improve resource efficiency, strengthen resilience and secure social equity. However, the principle about strengthening resilience is largely based on biophysical characteristics (biodiversity, synergies, animal health, soil health), while social resilience is only seen through the lens of economic diversification. The scope of this tool is somewhat limited to the farm level. F-ACT (Colbert, 2019) nevertheless features qualitative questions and proposes to rate each response from 0 to 3, with a corresponding description of what the answer needs to be to fall into each category. This enables the scoring of the overall agroecology of the farm which can provide useful insights. Another tool, the FarmTree Tool (Farm Tree, 2022) displays more quantitative features with the outcome of the tool being presented through graphs. However, again, it largely focuses on farm level socio-economics in its assessment of the social side of agroforestry. The FarmTree Tool (Farm Tree, 2022) further guides on the design of land plots and a selection of species needs to be made in the model to get more tailored results. However, only four tree species are included, as well as only four crops. This may hinder the possibility of the model to adapt to different soil types. The Social Benefits from Carbon Forestry Guide (Hadju and Engström, 2019) offers more practical insight into the social side of agroforestry, and allows project developers, through qualitative questions, to reflect on the benefits and risks associated with their projects. However, this tool is limited to the scope of carbon capture related actions. As such, a gap remains among current tools to assess agroforestry as a pathway to climate resilient development.

The aim of this paper is to examine agroforestry as a way to operationalise climate resilient development. In doing so, we develop a new tool to scope and assess agroforestry projects for their climate resilient development potential. Two objectives support this aim using mixed methods. Objective 1 reviews the literature on climate resilient development pathways and agroforestry to gain insights into how the topics relate to one another. Objective 2 draws on this information and develops and evaluates a tool for use by agroforestry stakeholders to develop (scope and assess) agroforestry projects that foster climate resilient development. While many existing tools look at agroforestry from an agro-ecological or environmental perspective, we specifically include socio-economic and governance considerations. Overall, we shed light on the important qualitative questions to be taken into account while designing, implementing, and evaluating agroforestry projects in the Global South for their climate resilient development potential, with particular focus on smallholder farmers. To the best of our knowledge, this is the first attempt to operationalise climate resilient development pathways through a focus on agroforestry.

In section 2, we introduce the framework developed by the IPCC on climate resilient development pathways. After describing our research methodology in Section 3, we present the results of our analysis in Section 4. Section 5 discusses the main aspects emerging from the analysis and concludes by directly addressing our aim.

2. Climate resilient development pathways

This paper uses the IPCC framework on climate resilient development pathways (CRDPs; Schipper et al., 2022) as the starting point for the development of a tool for stakeholders who want to launch/fund agroforestry projects in the Global South. CRDPs are defined as reactive and/or preventive actions that key stakeholders (e.g., government, business, and civil society) can take to become more resilient in the context of a changing climate while not compromising their development or increasing emissions (IPCC, 2022). This dynamic process is highly context-specific, with actions and solutions tailored to suit particular local needs. CRDPs support systems to retain their overall functionality and productivity through change, even though this may materialise over different timeframes. The main difference between climate resilient development and CRDPs lies in that pathways define a deliberate context-specific set of actions developing over time against a certain supporting system (financial support, national support and targets, legislation, international agreements, institutional support and expertise) with specified results (climate resilient development). Climate actions are all the transformations/changes/adjustments happening in the system. Resilience is built from the multiple actions, enabling communities to keep on thriving over time, even when facing increased climatic variability. Development is a result of all the transformation and the built resilience, enabling communities to keep on thriving socially, economically and environmentally. The structure (supporting system and actors) is the necessary envelope keeping things on the agreed pathway, making sure that progress is made and that targets are reached according to a structured context-specific plan. Without the supporting structure, attaining climate resilient development would not be possible. CRDP also depends on the existing system. The existing system needs, therefore, to be both engaged in and support the transformation (Birkmann et al., 2022; IPCC, 2022; Schipper et al., 2022). Figure 1 presents an illustrative CRDP, using agroforestry in all its forms to indicate sets of context-specific actions.

Building on one of the most recent IPCC reports (IPCC, 2022), CRDP can be attained through specified pathways, whereby societal choices about adaptation, mitigation and sustainable development manifest themselves within multiple arenas, through interactions between key actors (civil society, private sector, and government). Those mentioned societal choices are referred to as 'enablers' encompassing knowledge diversity, equity and justice, inclusion, and ecosystem stewardship. These enablers manifest themselves across political, economic and financial, ecological, knowledge and technology, socio-cultural, and community 'arenas of engagement' (see Table 1) where actions and social interactions are performed in directions that support CRDP and the pursuit of sustainable outcomes (IPCC, 2022). This paper combines the four enablers and the six arenas of engagement, making them more concrete and actionable, through a focus on smallholder farmer agroforestry projects in the Global South.

3. Research methodology

This paper is an exploratory conceptual study that charts new ground by examining how smallholder farmer agroforestry projects

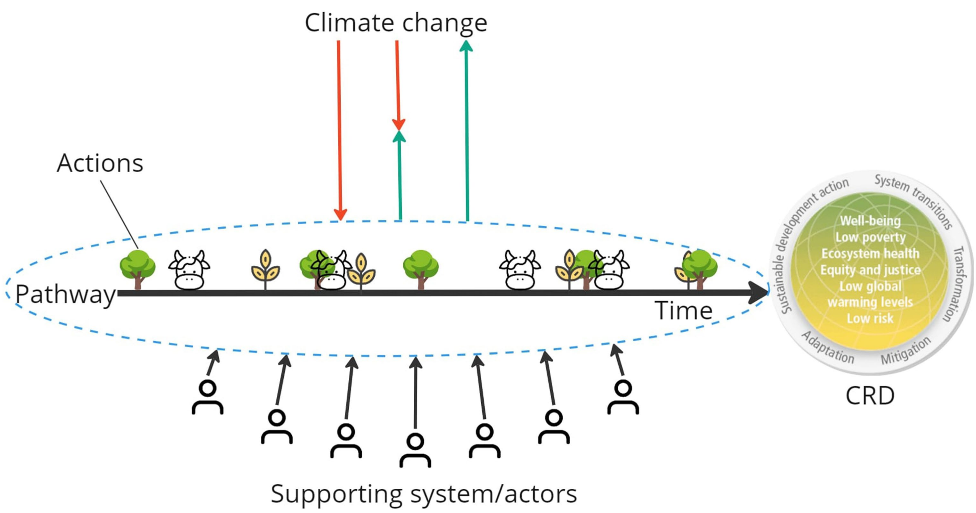

FIGURE 1
Visualisation of an indicative climate resilient development pathway. Black arrows represent support provided by different actors. The blue dotted line represents the decision-making space shaping the pathway. Actions for climate adaptation, mitigation, and development are represented by trees, hay stalks, and cows, showing how agroforestry can limit the impact of climate change on smallholder farmers (red arrows), while adapting to (interlinked green and red arrows) and mitigating the changing climate (green arrows).

TABLE 1 Definitions of enablers and arenas of engagement (authors' own).

	Enablers		Arenas of engagement
Knowledge diversity	Combining different types and forms of knowledge in a way that is acceptable, relevant and useful for stakeholders	Political	Power interplays between various levels of governance involving a wide array of actors
Equity and justice	Making sure that the process is fair and that the outcomes are fair [desirable] and good for humans and nature as a whole	Economic/ financial	Multi-level financial and resources fluxes and their use (investments, subsidies, loans, credits, taxes, incentives…)
Inclusivity	Ensuring that nature's and human's current and future stakes and interests are included in the process	Ecological	Environment in which a given society evolves and society's interaction with this given system (in face of climate change)
Ecosystem stewardship	Empowering communities to responsibly use and safeguard ecosystems through the uptake of sustainable practices	Knowledge/ technology	Existing/development/in-the-making knowledge and technology and their use
		Socio-cultural	Sets of norms and values shaping individual and group perceptions of the world (visions of the future, beliefs, attitudes, values, emotions, actions…)
		Community	Interactions between and among people sharing worldviews, values and behaviours at local, regional and global levels

in the Global South can operationalise CRDPs. The methods applied are mixed and largely qualitative, with the inclusion of descriptive statistics, as relevant (Figure 2).

3.1. Semi-systematic literature review

A comprehensive, semi-systematic literature review was conducted to understand how the enablers and arenas of engagement manifest themselves in publications on agroforestry and smallholder farmers in the Global South. As mentioned by Snyder (2019) 'The aim of a systematic review is to identify all empirical evidence that fits the pre-specified inclusion criteria to answer a particular research question or hypothesis'. In the context of our study, this was not possible since neither 'enablers' nor 'arenas of engagement' are explicitly addressed in the literature. Rather, we manually searched for more subtle references to 'arenas of engagement' and/or 'enablers', guided by our definitions. We therefore performed a semi-systematic literature review to allow more comprehensive analysis, which was not possible with only a keyword search. The publication time boundaries of the papers were defined between 2015 and 2022, the article language as English, and no specific spatial boundaries were set. The reason for selecting 2015 as starting date lies in the fact that in this year the Paris Agreement was agreed upon, whereby signatory nations agreed to

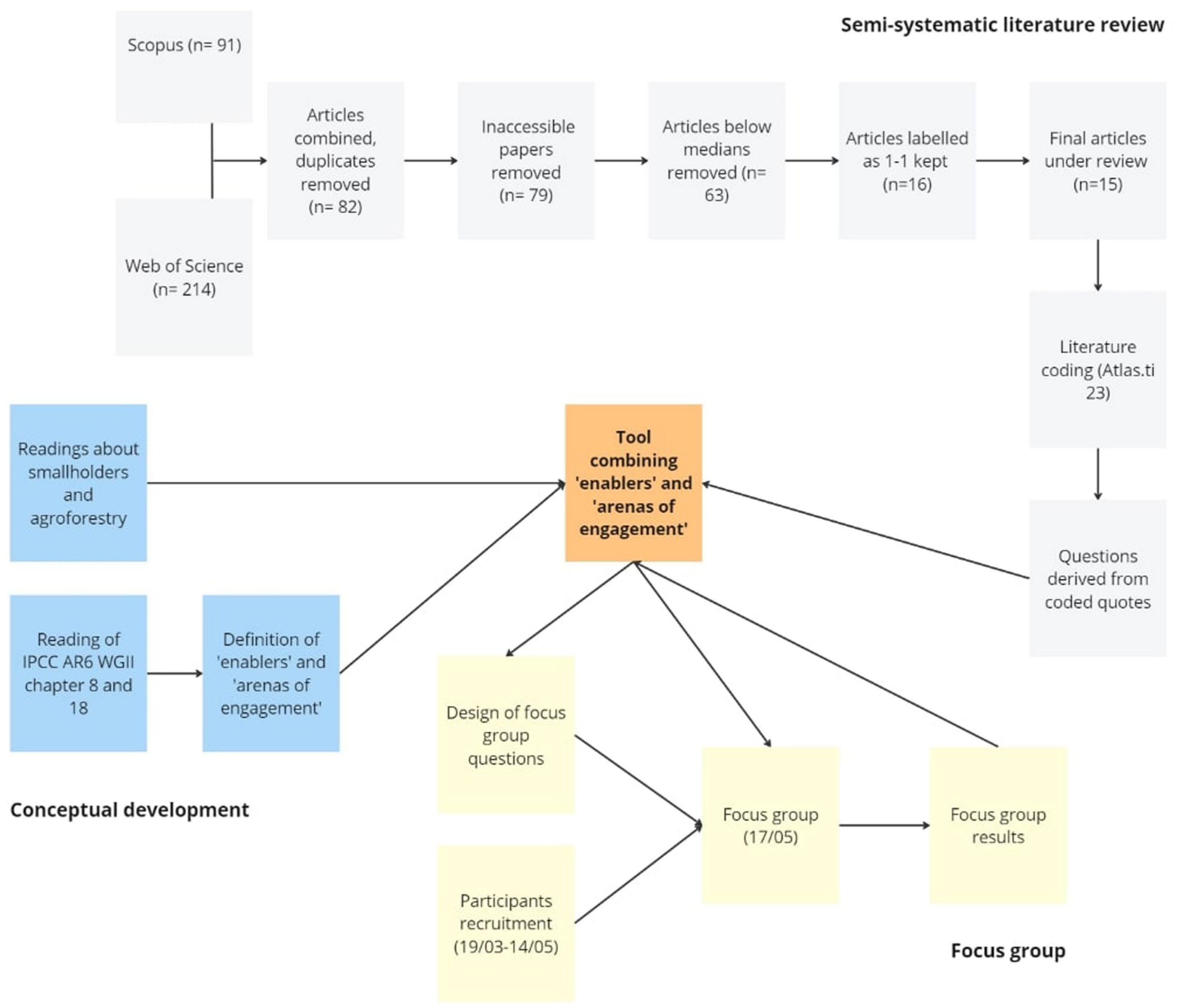

FIGURE 2
Flowchart showing the research process and methods used.

work towards climate resilient development. We deliberately chose to not set geographical boundaries so as to not exclude any articles from the Global South and to ensure the tool we developed can be broadly used across different geographical locations.

Next, we came up with the preliminary definition of search strings (see Appendix A1). The same search strings were used multiple times with 'community' replaced by each arena of engagement labelled as follows: 'political', 'economic and financial', 'ecological', 'knowledge and technology', and 'socio-cultural'. Considering the initial number of hits for each arena of engagement and for each enabler, some search strings were broadened, narrowed or changed accordingly (see Appendix A2). Finally, adjustments were realised after the second search round to be more encompassing (see Appendix A3). The following final search strings were used: agroforestry AND (1–6) AND (A-D) AND smallholder* (Table 2).

Search strings were then entered into Web of Science and Scopus. Because we wanted to see how the 'enablers' and 'arenas of engagement' were addressed in the literature, we considered it important to have only peer-reviewed articles in our analysis, thus ruling out the use of Google Scholar. Web of Science was chosen as an appropriate database in that it covers a wide range of subjects, which was needed for our research. Scopus was used to broaden the results, and enabled us to include articles that were not listed in Web of Science, while using the same search strings. Results from the two databases were combined in Excel (2016). Figure 2 presents the process of inclusion and exclusion of the literature. All article links were checked and a manual duplicate

TABLE 2 Final search strings (arenas of engagement and enablers).

	Arenas of engagement		Enablers
1	Poli*	A	Environment* empower*
2	Economic/financial	B	Fair*
3	Knowledge/technology	C	Knowledge diversity
4	Ecological	D	Inclusion*
5	Community*		
6	World-view*		

*as used in Boolean search, is a wildcard (i.e. Boolean operator) enabling the inclusion of other forms of the keyword to which it is appended.

check was carried out. Of the identified 83 papers, three were inaccessible and one was duplicated. The sample size was 79 papers at this point.

Papers were next screened using 'smallholder' and 'agroforestry' as search terms, allowing removal of papers that did not mention agroforestry. Frequency counts for these terms were indexed in Excel (2016). At this stage, no paper was removed. However, papers with a low number of mentions (between 1 and 4) of 'agroforestry' or 'smallholder*' mostly had those hits in the reference section, and not in the main text. This was addressed by calculating the median and quartiles of 'agroforestry' and 'smallholder*' mentions per article. This method was preferred to using the mean because of the extreme ranges of mentions (0–229 for 'smallholder*' and 0–349 for 'agroforestry'). Most papers included frequencies of mentions in 10 rather than 100. Also, the use of the median and quartiles was more objective than consciously altering the average when not taking into account the extremes. The obtained median for smallholder* was 11, while the median for 'agroforestry' was 16. Papers with frequencies of search terms less than or equal to the median (all papers ≤11 for smallholder* and all papers ≤16 for agroforestry) were labelled as follows:

- 1-1 = > median *2.
- 1-0 = > median smallholder.
- 0-1 = > median agroforestry.
- 0-0 = < median *2.

Papers marked 1–1, 1–0, and 0–1 were kept, and for the sake of not getting rid of relevant papers, the 22 papers labelled 0–0 were scanned through, of which six made it to the next step following further screening. The result was: 79−(22–6) = 63 papers.

All 63 papers were then imported into Atlas.ti 23. However, after reading through seven randomly selected papers from the sample, we realised some may still not be entirely relevant to our research because they did not clearly focus on agroforestry for smallholder farmers, with 'agroforestry' and/or 'smallholders' being mentioned only a few times throughout the papers. We, then focused on the 16 papers labelled as 1–1 (above median hits for both 'agroforestry' and 'smallholder*'). Of these 16 papers, 15 papers were reviewed through an in-depth semi-systematic analysis process. The 16th paper was excluded as it was out of scope following thorough reading: it addressed the correlation between bird species and population on land use variations (including land used for agroforestry). Coding of all the selected literature according to the enablers and arenas of engagement then ensued, with codes exported into Word (2016) for further analysis. The extended analysis entailed the formulation of questions raised by the papers which agroforestry projects could usefully consider. These were placed in a 24-cell table and formed the basis for development of the tool (Appendix C2).

3.2. Focus group

Potential participants for an online focus group (on Zoom) were contacted as early as 29 March 2023 for a session on 17 May. This was complemented by a snowballing approach whereby potential participants forwarded the invitation to other interested parties. We targeted between 6 and 12 participants from representing different types of stakeholders and perspectives. In total, 10 experts participated in the focus group, coming from six countries, four of which are in the Global South (Nigeria, Kenya, India, Indonesia), and two in Europe (Sweden, and France). Participants were mostly from academia (8/10), while two practitioners working from Kenya and Indonesia also took part in the discussions (see Appendix B1 for more information). Timing was sensitive to the time zones of the participants, to be as inclusive as possible and participants were given access to the draft tool 3 days ahead of the session (see Appendix C1).

The 2-h session opened with participant introductions. The draft tool was then briefly presented, followed by discussion of four open-ended questions (Appendix B2). Two people took notes in the discussions, while the session was also recorded, in line with ethical approvals granted by the lead author's institution which required free, prior informed consent to be given by participants. Focus group results were bundled by themes that emerged from the discussion, and the tool was revised in light of their comments.

3.3. Study limitations

Limitations of our study generally encompass the: (1) scope of the research, (2) limited representability, and (3) translatability. The scope of our research is limited to peer-reviewed articles, and does not include grey literature reflecting on regulations and or actions towards CRDP in agroforestry. In addition, search strings did not account for specific terminology used to describe the various forms of agroforestry. The papers we reviewed mostly covered agrisilviculture as a form of agroforestry. As such, the tool we developed may not cover agroforestry to its full extent. The final selection of articles under review was limited to 15 papers. We can assume that the literature on agroforestry and smallholder farmers, which touch upon components of CRDP may be broader. While we recruited participants for the focus group a long time in advance of the focus group itself and looked to have a diverse panel, most attendees were academics. This limited field-based insights in the discussion. Funders were also absent from the session, who may have helped us steer the tool more in the direction of topics funders would also see as prominent in the design of agroforestry projects for CRDP.

4. Results

4.1. Literature review

Figure 3 shows the breakdown of the sampled literature according to the year of publication. The majority of the papers from the reviewed literature were published in the past 5 years. Seven papers come from three journals: three in *Agriculture, Ecosystems and Environment*, two in *Forest Policy and Economics*, and two in *Land Use Policy*. The remainder of the sample papers were published in other journals.

Countries represented in the selected literature are fairly well spread throughout the Global South. Among the 15 papers, one focuses on Oceania (Melanesia), five on South Asia (India, Malaysia, two on Indonesia, and one comparing Indonesia with Bangladesh), three on Africa (Ethiopia, Sub-Saharan Africa, and Southern Africa), and four on Central and South America (Mexico, Nicaragua, and two

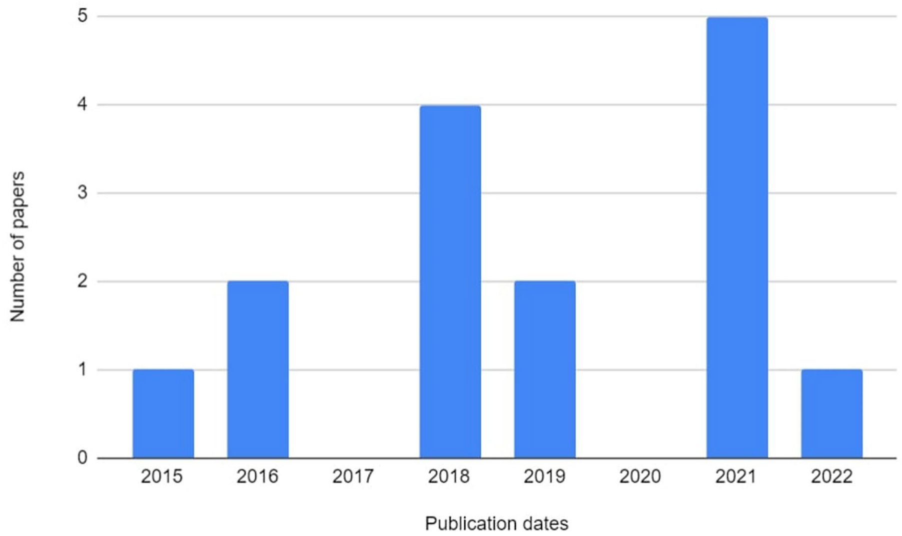

FIGURE 3
Number of papers per year since 2015.

on Peru). The last two papers have a more global focus, on low and middle income countries, and Meso-America and East Africa.

Based on the three major types of agroforestry (agrisilviculture, silvopastoralism, and agrosilvopastoralism; FAO, 2012), we examined which forms were most represented in the selected literature. The most common was agrisilviculture with 8/15 papers (53%) referring to this form of the practice (5, 6, 9, 10, 11, 13, 14, 15). This is followed by 3/15 papers (20%) tackling agroforestry more generally (1, 2, 7). Paper 7 discusses agroforestry in the wider agricultural system of climate-smart agriculture (CSA), therefore also taking other practices into account. Paper 4 is not categorised because of the limited information linked to the practice of agroforestry. Another mentioned both agrisilviculture and agrosilvopastoralism although later focused on agrisilviculture solely (3). Two papers did not fall so easily in the categories and focus on timber-agroforestry, which involves the felling of trees. These articles therefore differ from the rest of the reviewed literature for the business model they focus on, but also for the agroforestry benefits mentioned, with no focus on climate mitigation through carbon storage but rather on the sale or use of timber for local needs (8, 12).

The sampled literature concurs that smallholder farmers are vulnerable to food insecurity (5), whose vulnerability is increased by a changing climate, further marginalising this specific group (4). Shifting climate patterns put at risk smallholders' crops, which are often rain-fed and subject to little fertiliser (4, 7). Most smallholders rely on their crops to support their livelihoods (4, 5, 6, 12, 15). Moreover, their production is often limited (12) due to the small cultivable area they can access, but also due to the limited available labour, which is often limited to family members (15). Smallholder farms are often isolated (4, 6), with limited access to technology (4), and to the market (4, 5, 6). To access the global market more easily, farmers turn to high-demand commodities, such as cocoa, coffee, and palm oil (2, 8, 9, 10, 12). However, smallholders' income is often close to or below the poverty line (3, 4, 6), pushing them to look for off-farm work as a complement or replacement to farm labour (4, 6, 12). Although most definitions consider smallholders to farm landholdings of 1 to 10 ha (3, 4, 6, 7, 9, 11, 13), two articles, with a geographical focus on Peru, mentioned land holdings of up to between 200 and 400 ha (10, 12).

Appendix C2 presents the questions derived from the in-depth semi-systematic literature review. The number of questions per cell varies greatly, from 10 identified questions exploring the interaction of 'equity and justice' and 'economic/financial', to only one question for six of the other cells (economic/financial + ecosystem stewardship, ecological + inclusivity, ecological + knowledge diversity, ecological + ecosystem stewardship, socio-cultural + inclusivity, community + ecosystem stewardship). The sampled literature also focuses on certain arenas of engagement more than the others, with 'political', 'economic/financial', and 'knowledge/technology' receiving most coverage. The same can be said for 'equity and justice' as the most commonly addressed enabler. The following subsections zoom in to the main insights found in the literature, which guided the development of the questions and the drafting of the tool.

4.1.1. Barriers to the uptake of agroforestry by smallholders

One of the difficulties faced by smallholders is a lack of political support, which can take multiple forms. Barriers can take the form of new laws and regulations, binding smallholders to fulfil certain requirements (12), or exposing their constraints in complying with new requirements enforced by the government (3), disregarding challenges associated with smallholder farmers' capacity. Other reported barriers include a general lack of institutional support (1, 2) to make necessary investments or changes, and, in some places, absence of agroforestry policies supporting and regulating the practice (5). Finally, introduction of regulations on timber-agroforestry are seen as a further obstacle for farmers to adopt the practice because of the extensive, knowledge-intensive paperwork that farmers need to complete (12). One of the questions emerging from all the barriers associated with governments and institutions is that of the composition of the decisional agenda, as much for its content as for who influences it.

Another barrier to agroforestry adoption faced by smallholders is linked to funding, credit and financial capacity. Up-front costs are often associated with shifting farming practices to agroforestry with the purchase of seedlings, trees, and material, while at the same time, taking land out of agricultural production to plant the trees. The return on investment does not occur immediately, but after a few years (7, 8, 10), thus 'generating a negative flux of net benefits in the short-term' (7 p.12), which prevents smallholders from engaging in agroforestry. To cover for the yield losses while trees mature in the first years, smallholders would need to get access to credit, which is often difficult to obtain (1), not always culturally acceptable, and not all smallholders know about this possibility due to a lack of promotion of agroforestry linked to absence of policy support (1). In addition, some countries/institutions/organisations may not be completely ready for a massive investment in climate adaptation strategies, often viewing them as uncertain (2). This suggests that perceptions on climate adaptation need to evolve for new strategies to become socially acceptable and institutionally supported. A further issue is that while NGOs and other organisations have been investing in agroforestry through projects, they often have limited budgets, which once used up, result in termination of support to smallholder farmers. Discontinued funding is problematic in that it is not followed by long-term national funding, leaving smallholders to their own devices to maintain the trees. This has been found to limit the large-scale and long-term adoption of agroforestry (1).

One of the questions emerging from all the barriers related to financing and monetary capacity is whether funders/banks understand the situation of smallholders well before granting credits (i.e., acknowledging that the back payments may be delayed due to the temporality of agroforestry, as well as with fluctuating income of smallholders).

Contrary to other agricultural practices, agroforestry happens on a long time scale. Secure, continued land tenure is central to the uptake of the practice, as well as to its perpetuity, with one article (1) putting strong emphasis on secure tenure for agroforestry to develop: 'There are few agroforestry success stories in an uncertain land tenure context' (Borelli et al., 2019, p. 2 as cited in 1 p.3). Papers 8 and 12, which dive more in-depth into timber-agroforestry, also note that farmers are solely interested in changing their practices in a land secure context, and that the needed investments do not attract farmers who do not have secure tenure. Farmers often resist changing their practices to agroforestry when they do not own the land that they cultivate, an element which comes as an ancillary risk on top of the investment (6). To improve tenure security smallholders have also been found to join cooperatives as a means to by-pass this obstacle issue (13). One of the questions emerging from all the barriers linked to land tenure is that of whether smallholders are the tenants of the land on which they sustain their households.

Another barrier to the adoption of agroforestry as a main farming practice lies in the choice of species, which are often selected for their market prospects, rather than their adaptability to the local environment. This can lead to competition and incompatibility issues among and between species (9). Other issues may arise from the sole use of traded commodities from trees, with, for example, the degradation of local agrobiodiversity (10). Another issue may be the introduction of species largely promoted for benefits that they do not bring (5), which may, in turn, lead to misinformed ecosystem management, putting crops at risk of pests and diseases (14). To address newly emerging pests and diseases associated with climate change, hybrid species may be introduced (for example, an hybrid coffee species to combat coffee leaf rust in Mexico) (3), or other hybrids (4). Use of newly introduced species is often associated with the promotion of fertilisers (3), which may put a further burden on smallholders who not only have to change the species they are cultivating, but also invest in chemical inputs. This increases their dependence on external actors/inputs, reducing their autonomy and resilience (4). One of the questions emerging from all the barriers associated with species choice is that of whether the use of the new species or the farming technique poses a threat to the overall existing system in which they are introduced.

Agroforestry is described as a knowledge intensive practice, which requires multidisciplinary approaches (8), implying more than simple access to seeds or saplings (2). Successful agroforestry requires knowledge about nutrients and pruning (2), as well as seed quality, but smallholders are often unable to obtain information about the planting materials they can access (9). The literature also points to the need for farmers to know about the agro-ecological implications of planting certain species alongside others, to reduce the impacts of species competition (11). In addition, while information about mainstream commodities may be available to smallholder farmers, information about less mainstream species, which may be more appropriate to their farms, is largely absent, making the use of other species even more challenging (10). Another barrier is that smallholders often sell their products to middlemen, which they are at the mercy of, because farmers lack knowledge about fair pricing (1). One of the questions emerging from all these barriers linked to knowledge and information is that of whose responsibility it is to bridge these knowledge gaps.

4.2. Focus group

Focus group participants highlighted the suitability of our tool in including equity as one of the four enablers (FG1; FG2) noting the possibility to include everyone from a given community, including underrepresented groups, such as women and young people (FG3). Participants further suggested the need for gender to be considered more directly within equity concerns, as farm labour tends to be gender-specific (FG1), and rules and norms emerge from different genders (FG1; FG3). It was also suggested that gender dynamics should be taken into account in relation with trees (FG7) as the utility of the trees planted often differs according to gender. FG1 explained that a tool on gender equality and social inclusion was used in past research, but emphasised that tools need to consider equity, rather than equality. FG2 estimated that they unconsciously coupled equity ('how to make sure that smallholders can also feed their families') with the 'ecological' arena ('how to safeguard the environment and increase biodiversity') in one of his previous research projects, and concluded that it was essential to consider the two at the same time.

Questions about land tenure, land ownership, and land rights also came to the fore as another important topic to take into account when designing agroforestry projects (FG5; FG8; FG3), while participants suggested further consideration is needed of policy frameworks accompanying the adoption of agroforestry describing it as essential to understanding the contexts in which projects are taking place. Two experts (FG3; FG7) noted the absence of agroforestry policies in certain countries, while FG4 stated that even when policy frameworks exist, they are not completely supportive, although they have been in the case of India, with an observed boost in the uptake of agroforestry.

Participants' experience also showed that enablers need to be integrated into the overall approach taken by researchers/project managers. One expert (FG8) considered knowledge and training can be usefully combined in the context of ecosystem stewardship, giving an example of how knowledge and training was offered to smallholder farmers, building their skills to measure carbon stocks in order to access the carbon market. This training was considered one of the essential requirements for farmers to be able to join the carbon market (FG8; FG5). It was further mentioned that measuring developments in agroforestry could not be achieved if the social dimension was not taken into account (FG2), therefore encouraging the use of our tool, which offers to combine different enablers to arenas of engagement.

Of the eight experts who orally took part in the discussion, five found the tool to be relevant, useful, and/or important (FG1, FG2, FG3, FG5, and FG7). FG9, who participated through the Zoom chat also mentioned that the 'tool is useful for monitoring and evaluating' projects. Usefulness was, however, qualified as an indirect usefulness to the experts, themselves. As most participants were academics, they did not see the tool could directly benefit/influence their research, but saw it as relevant to agroforestry project developers and funders, in the form of a 'checklist' (FG1; FG5). It was also perceived as a useful way of 'prioritising' (FG7) the social dimension of smallholder agroforestry through qualitative evaluation, instead of quantitatively measuring parameters, which is often difficult (FG5; FG7). In that sense, the tool we developed was considered potentially 'more receptive to the realities on the ground' (FG1) compared to other tools previously used in research projects, and as something that could be 'adapt[ed] to the local context' (FG3).

4.2.1. Critiques/concerns

Finally, while it may be a strength that our tool is not context-specific in its design, it may also be a weakness. Indeed, the limited context-specificness of the tool signifies that major interpretations and translations will be needed to adjust to the relevant local situation.

Critiques of the tool coalesced around: (1) concerns that the breadth of the questions leaves them open to misuse as a justification for implementing harming actions/projects, (2) concerns that the tool seems to solely account for project initiated agroforestry rather than that directly coming from the farmers, and (3) the tool has not yet been used in practice.

FG5 worried that the 'vagueness of the questions' makes it 'easy for the people who have the power to interpret the question in a way that is good for them'. While the same expert considered the tool useful to help agroforestry projects to formulate how they will take various parameters into account, they also voiced concerns over the manipulation of what is said, and how it is said. This highlights a potential risk to the use of the tool, which could benefit those already profiting from smallholders, leaving the latter group unaided.

The tool addresses agroforestry from a project-led initiative and the extent to which it could be useful to other groups was considered to be limited. In some countries, such as India and Indonesia, agroforestry is not always initiated through NGOs or funding agencies, but by farmers themselves, supported by policies encouraging agroforestry as the main farming practice (FG4; FG6). Another expert (FG8), suggested that in many cases in Indonesia, the land was owned by the government, and land access was granted to farmers. The tool was therefore seen as not reflecting/accounting for a sufficient variety of contexts (individual agroforestry projects, NGO-led projects, community-led projects, and so on).

Finally, the tool may lack direct usability in practice as it has not yet been field trialled by agroforestry project developers. As indicated by FG6, the tool also does not give an indication of when an agroforestry project is good to go, even if all questions have been addressed. There is no benchmarking through, e.g., numbers or colours to indicate whether the results from the pre-study at the design phase of a project would contribute to climate resilient development (FG6). FG6 reiterated twice that the tool was 'too big'. This can lead to misunderstandings about its purpose. For example, FG4 thought that market access was not taken into consideration into the tool, yet this is mentioned at the intersection of the 'economic' arena of engagement and 'inclusion' as an enabler. It is possible they got lost in the size of the tool, which demonstrates that it needs field-testing and further adapted to use more easily in practice.

Table 3 combines the results from our research and seeks to integrate as best as possible the critiques raised through the focus group.

5. Discussion and conclusion

5.1. Agroforestry and climate resilient development pathway

Agroforestry is presented here as a potential pathway, capable of adapting to and mitigating the effects of climate change, while promoting development. It offers ways of adapting to climate change through more diversified crops (Mbow et al., 2014) rather than monoculture. Mixed species, which is the case of agroforestry, are considered less risky than monoculture in the sense that if a pest appears, its spread may be limited to one species. Loss is thereby reduced, and other commodities than the failing crop sustain agricultural yield. This in turn enhances the adaptive capacity and reduces the vulnerability of smallholders, thus increasing their resilience to climate change (Quandt et al., 2023). Also, the diversified production of agroforestry offers important socio-economic prospects to smallholders. When a crop fails, farmers can still sell tree products for income, or consume their own products to sustain themselves. In addition, agroforestry has the potential to mitigate climate change as trees absorb carbon while growing. This is particularly relevant because limiting further warming through the uptake of carbon may limit the extent to which smallholders will be put at risk by extreme climatic events (such as prolonged or more frequent droughts, heavy rainfalls, ...; Verchot et al., 2007). Reducing this risk is important as they already face the heavy burden of sustaining their household solely through the cultivation of their land and have very little income to buy extra food. Agroforestry would therefore positively impact two of the objectives of CRD: low global warming levels, and low risk (IPCC, 2022). Increasing the overall stability associated with the smallholding environment may therefore help farmers better cope with the already existing burden from climate change, whereas more diversified diets, diversified sources of income and other social benefits associated with agroforestry (e.g., on-farm wood gathering, more shadow, medicinal properties of the trees) will help them keep thriving and developing. The implementation of agroforestry bodes well for smallholders as it

TABLE 3 Revised tool integrating information from literature review and focus group data.

	Equity and justice	Inclusion	Knowledge diversity	Ecosystem stewardship
Political/ Decision-making	• What is on the agenda? • Who is benefiting from this decision/policy? • Is the policy/project a short term quick fix or is it meant as a long-term planning/resilience building? • Is this policy/project desirable for smallholders or harming/burdening them? • Is smallholder resilience valued? • Are laws supporting the implementation of agroforestry or limiting its generalisation? • What are the powers at play?	• What is on the agenda? • Who is benefiting from the project/policy? • Are farmers represented or are they directly participating? • How open to discussion is the decision-making forum (democracy, repressive power, dictatorship)?	• Is local knowledge weaved with scientific knowledge to help convince smallholders to transition to agroforestry? • Is external knowledge combined with local knowledge to guide farm decision-making? • Are agenda points justified by needs/demands from all or only fuelled by individual wills or power groups?	• Is this project/solution a quick fix or is it going to help with resilience building? (→ What is on the agenda) • Are legal texts helping the promotion of agroforestry or hampering its uptake altogether? • Who is taking action? • Is the project/policy/regulation empowering smallholder farmers to take care of the environment?
Economic/ financial	• How is money used? (→ What is funded and what is not? & What is the purpose of the investment?) • How accessible is the market? • Who is making profit? • Can farmers cover up for the up-front costs associated with the project? • Are the prices of material (seeds, trees, equipment) low enough that farmers can afford them? • Is there a market for smallholders' products? • Is the funding secured for a long time period or only destined for a short period of time? (→ What happens beyond the project when managers run out of money?) • Does the project/investment help smallholders make a living income or burdens them financially?	• Who has the money? (→ Who is investing and what are the motives behind the investment?) • What are the conditions/requirements to receive funding? • Can farmers afford the proposed solutions/technologies? • To what extent do smallholders have a say in the market? • Can farmers easily access the market to sell their products? • Are certain groups excluded from generating economic value? • Who is benefiting from the generated economic value?	• Do funders/banks understand the situation of smallholders well before granting credits (i.e., acknowledge that the back payments may be delayed due to fluctuating income)? • Do smallholders know about the available financial mechanisms they can have access to? • How is money invested (e.g., research and development, communication platforms, education, ...)?	• Are farmers equipped to protect the environment or are their investments making them more reliant on external input (chemicals) damaging the environment and reducing their autonomy? • Are investments targeting training farmers to safeguard the environment/promoting new (more sustainable practices)/new machinery, tools, and technology?
Knowledge/ technology	• To what extent is external information/scientific knowledge appropriate/fit to the local context? • How do farmers get the necessary skills to the proper realisation of agroforestry projects? • Is knowledge/technology physically and financially accessible? • Are there any threats associated with the introduction/use of this technology (species, equipment, planting material, chemicals, ...)? • How suitable/adapted is the technology to the local context? • Whose responsibility is it to bridge knowledge gaps when they are identified? • Who is providing for the material? • Are institutions promoting the use of new knowledge and technology?	• What are the conditions to join in the training activities? • Is the training integrating both local and scientific knowledge? • Under which condition is cultivating material, seedling, ... made available to farmers? • Do the farmers have sufficient pre-existing knowledge and enough financial capacity to access and use the technology? • Can all farmers access the necessary technology (e.g., smartphones) to obtain knowledge about the market? • Are institutions promoting the use of new knowledge and technology to all or to only to identified groups? • Are knowledge/technology intelligible/user-friendly to everyone or are they exclusive? • Who decides which technology to use?	• What is the place of local knowledge in the discourse farmers hear? • To what extent is local knowledge taken into consideration when external actors come? • Whose knowledge/know-how/skills are used in the projects? • Is the training weaving both local and scientific knowledge? • Does the introduced knowledge/technology build on pre-existing knowledge or introduces completely new knowledge and skills? • Is the introduction of new technology backed up by appropriate training?	• Does the introduction of this knowledge/technology cause any threats/dangers?/Do we know enough to apply the technology? • Is the species well adapted to the local context? • Are farmers empowered to protect the environment through the knowledge/technology they have access to? • Do farmers have enough leeway to experiment and adjust their practices, and develop new local knowledge?

(Continued)

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TABLE 3 (Continued)

	Equity and justice	Inclusion	Knowledge diversity	Ecosystem stewardship
Ecological	• Does everyone have access to the forest/land? • How easily accessible is the forest/land? • How can farmers benefit from forest products? • Are the best adapted species grown? • Which species are promoted? • Where does the benefit lie (global level, local level)? • Are the actions geared towards protecting the environment also good for people?	• Do all farmers have access to land? [Is land tenure secured?] • Is the project accessible to all or exclusive with selection criteria, investments, ...? • What are the means to deal with the barriers to land acquisition?	• Do farmers know about the nutritional requirements of the introduced species? • What is the state-of-the-art in terms of agro-ecological knowledge and local soil condition knowledge [overlaps or knowledge gaps]? • Do farmers need to receive training to plant and maintain trees better? • Is local knowledge about soil conditions taken into account in the design of the project?	• Are the introduced species further burdening the farmer through expenses (e.g., fertilisers, tree species with high maintenance costs)? • Is the land/forest handled sustainably (i.e., is it exploitation compatible with current and future conservation and use?)
Socio-cultural	• To what extent is smallholder resilience viewed as important? • What is valued and is this value shared or diverging among actors? • Are there crowd-out effects where organisations take a significant share of the responsibility to help smallholders, leading to more inaction from another actor? • Who is taking responsibility to help smallholder farmers?	• Is agroforestry acceptable to farmers or is it radically hindering their local agricultural identity (e.g., seasonal crops, garden farming, ...)? • Are smallholders' challenges and worldviews at the core of the project design? • Do existing cultural and social norms allow for equal participation in all forms of agroforestry?	• What is the story told to farmers when they are approached to join the project? [what is considered as important and whose values and perceptions are dominating?] • Are knowledge and experience about agroforestry shared to increase the perceived value of agroforestry?	• Which products/services are valued by the farmers in the trees? • Which tree species are valued by the farmers? • What motivates farmers to protect the environment and maintain the trees?
Community	• How beneficial/desirable is it for farmers to join a certification scheme/partnership through cooperative networks? • What is the role of local communities/networks in supporting smallholders? • Who is benefiting from the collaboration?	• Are there any conditions to join cooperatives/ partnerships? • Are cooperatives/farmer associations well integrated in the supply chain? • Are the interactions between actors benefiting the community as a whole or to specific groups only?	• What kind of information is shared between smallholders? • How is the information shared? • Whose perspective is considered important in the interaction?	• What is the common vision the community shares that encourages them to safeguard the environment? • Are farmers ready to adapt their practices to protect the environment better? • Are farmers empowered to change their practices to agroforestry?

The tool considers the enablers and arenas of engagement interactions in agroforestry projects, contributing towards the operationalisation of agroforestry as a climate resilient development pathway (This informative tool was designed to help project developers/ funders design and evaluate their agroforestry projects before its beginning, during the project, as an evaluation/monitoring tool, or at the end of the project to identify and learn from the project's successes and failures for future project development.).

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could offer the triple-win associated with CRD, that is climate change adaptation and mitigation, and development.

Agroforestry, however, also comes with challenges that should not be overlooked when pursuing CRD. For example, farmers may regard the years they lose while waiting for young trees to grow and produce as a net loss even though, over time, more diversified production will offer new potential sources of income (Lasco et al., 2016). The temporal and spatial aspects of agroforestry are therefore a challenge to the nutritional and economic stability of smallholder farmers. To avoid further burdening smallholders with the challenges inherent to the implementation of agroforestry, especially the net losses associated with the early implementation phase, it is essential to implement up front monetary compensation. This could take multiple forms such as governmental or organisational subsidies, bank loans, or delayed payback time for credits.

Another challenge agroforestry faces is that solely planting trees with high carbon storage capacity, which may be desirable to further mitigate climate change, may not be the best option, even though the new trees may improve local biodiversity (Jose, 2012). The ability of the selected species to adapt to the local context, including the climate variabilities it may experience, is also crucial. Coe et al. (2014) discuss the limited success of agroforestry projects which fail to account for local specificities. This is of major importance. When incompatible species are introduced, they may enter into competition with native species for nutrients, light (Ollinaho and Kröger, 2021), and water (Miller and Pallardy, 2001), leading some native species to die out or their yields to diminish (Santos et al., 2012 as cited in Ollinaho and Kröger, 2021). Not only can species misadaptation lead to environmental consequences, which undermine the health of local ecosystems, but it can also directly impact the capacity of smallholders to sustain their livelihoods. Because of diminished yields (competition for nutrients, introduction of pests) or increased expenses for chemicals, needed to compensate for the imbalance in nutrient distribution, smallholders may be at an increased risk of poverty, which would pose a direct challenge to the pursuit of CRD.

While agroforestry may provide climate mitigation through the uptake of carbon and may help farmers produce highly traded commodities (coffee, bananas, or mangos), the introduction of agroforestry needs, first and foremost, to reflect local needs and demands. If there is no local impetus to adapt practices or improve the agricultural system, the desirability and the fairness of the project may be significantly reduced. As Coe et al. (2014) discussed, the general local context must be taken into consideration, not solely the biophysical dimension, but also the social, economic and institutional conditions. Project designers and funders will therefore find it all the more important and relevant to pay attention to local aspirations as well as the context in which they exist. In some cases, for instance, smallholders have access to opportunities for funding such as subsidies from the government or NGOs, to practise agroforestry. As mentioned by FG4 and FG6, in other places, such as India and Indonesia, it is more common for individuals, supported by adequate policy frameworks, to initiate agroforestry projects. For example, in India, agroforestry is supported by a complete legislative framework, which encourages its implementation (*cf.* Government of India, 2014). In other contexts, however, financial help may not be available, leaving farmers to bear the costs associated with the initial investment. For CRD to be successfully pursued, these discrepancies need to be duly considered. Otherwise, the capacity of the project to reflect equity and justice at the local level where the project is implemented may be jeopardised. Our tool is holistic, rather than normative, and considers the multiple arenas of engagement, while allowing for particular enablers to be reflected more significantly, depending on the stakeholder preferences. FG7 suggested that our tool gives space for prioritisation instead of measurement, which may be more to the point when it comes to understanding how the components of CRDP play out in the local context. In addition, it is perceived as a tool that offers potential for social learning, whereby different stakeholders prioritise and discuss the different enablers in combination with the arenas of engagement. The process could offer a forum for smallholders to voice their expectations and concerns, helping project designers to explain how the different topics covered by the questions were taken into account in the project design. The tool was therefore seen as offering a means for project designers to explain what they intend to do in light of the local context (FG5).

Given these concerns, while agroforestry can be seen as a potential strategy through which climate resilient development could be operationalised, thereby contributing to climate adaptation, mitigation and development, its introduction is not without risks. Agroforestry as a farming practice calls for the careful consideration of species as well as more than the prime consideration of economic returns through selling agroforestry products, and also the consideration of potential social risks emerging from the practice. Overlooking the risks and trade-offs inherent in agroforestry may undermine the benefits it also brings about in terms of climate mitigation and adaptation, and development. As highlighted by Stringer et al. (2022), pursuing CRD is not a matter of whether or not trade-offs exist in the chosen pathway of action but rather a matter of acknowledging them to address them adequately. To do so, the chosen pathway needs to offer sufficient space for iterative discussion and decision-making between the different stakeholders, which will evolve throughout time to better reflect the local challenges. This is where we see that the support the pathway receives is crucial, both from the farmers and the project developers and funders, but also from the governmental and financial institutions as these challenges need to be addressed by all stakeholders through joint actions. This resonates with Eriksen et al. (2021), whose work emphasised that adaptation and development cannot be reached by non-targeted work engaging with one sole group of actors (e.g., smallholder farmers) while the system continues to go against the transformation initiated through projects and local actions; rather the whole system needs to support the action for it to successfully pursue CRD. We can imagine that our tool could be used as a communication platform between the various actors from the project, which could help build the supportive system on which the indicative pathway towards CRD relies.

5.2. Contribution to the literature

Our study contributes to the emerging body of literature on Climate Resilient Development Pathways (CRDP). We operationalised CRDP through agroforestry as a farming practice for smallholder farmers, and developed a tool for project developers and funders to use to check that their project is aligned with the goals pursued through CRD. Our tool takes the multiple objectives associated with

CRDP into consideration (climate adaptation and mitigation, and development) while also making sure that the trade-offs linked to agroforestry are duly taken into account to ensure that CRD is pursuable. In that sense, our tool has the potential to help developers and funders check that the project is suited to the needs of farmers, and that it will be benefiting them, without putting smallholders at further risk of nutritional and economic poverty, which would be contrary to the pursuit of CRD. Although our tool may be important to the literature, it was not without difficulty that we were able to build it. One of the biggest challenges was the current lack of CRDP language in the literature, with the literature not mentioning 'enablers' and 'arenas of engagement'. As such, our research contributes to expanding the current literature on CRDP, and may be used as an exploratory study upon which further studies may be built. We also developed a tool, which is potentially more advanced than other tools in taking the social dimension of agroforestry projects into consideration and which allows explicit consideration of the interactions between the enablers and arenas of engagement in pursuit of climate resilient development. Indeed, in comparison to other tools developed to assess agroforestry, our tool is more holistic, and can be adapted to various forms of agroforestry in different contexts. As such, our tool contributes to the body of literature around CRDP as, to the best of our knowledge, it is the first operationalisation of the concept.

5.3. Policy implications and future research

The CRDP, as developed by the IPCC, was incorporated in the summary for policymakers, but not delivered with adequate explanations enabling the conversion of scientific knowledge into actionable policy making. Additionally, considering that only the most central information is included in the summary for policymakers, the CRDP framework was therefore seen as an important concept to research. This study, therefore, serves as clarification of the framework through the definition of CRDP itself, enablers as a concept, arenas of engagement as a concept, as well as every single enablers and arenas of engagement. Our research also acts as an exemplification of the use of the CRDP framework through agroforestry as a potential pathway.

Although validated by researchers and practitioners during the focus group, and by the researchers team in a separate case study, the tool may be further applied for validation and reflections. Follow-up research may also involve the development of an evaluation grid that could help measure the extent to which projects actually strive towards CRDP according to the questions we developed. This could be achieved through a combination of comparative case studies of past and present agroforestry projects for smallholder farmers, in similar and varying climate regions. It may also be valuable to further inquire about the development of a supporting system for CRDP. Studies could, for example, focus on the role of governments and financial institutions in the development of the needed structure.

6. Conclusion

This paper has presented an exploration of the operationalisation of climate resilient development through agroforestry. We have seen that agroforestry projects require careful attention to multiple elements to ensure that its uptake is not harming the environment and not making smallholders more vulnerable (i.e., that it really is building climate resilience). Our study shows that attention needs to be paid to species selection, local biodiversity and soil composition to avoid any form of competition between trees and crops for nutrients, light, or water. In addition, we noted that the introduction of non-native species, when those are invasive to the place where they are introduced, can be detrimental to local ecosystems and food production. We highlighted the social challenges associated with agroforestry projects, where gender dynamics, labour division, social perceptions and fears need to be addressed. Our findings also emphasise the prominence of the local context and the need to consider social, economic and institutional conditions in the design of locally tailored agroforestry projects. In this respect, the tool we developed as a combination of enablers and arenas of engagement to pursue CRDP through agroforestry is useful. It provides a way for project developers to comprehensively check that their projects are taking the multiple dimensions of CRDP into account. It also allows project developers to explain how they intend to take CRDP components into consideration and how the project aims to align with local needs to maximise the potential benefits of agroforestry projects. Compared with other tools, ours provides features that permit greater reflection on the social dimension of agroforestry projects. Through the case of agroforestry, this study, therefore, contributes to the understanding and operationalisation of climate resilient development pathways as a farming practice for smallholder farmers.

Data availability statement

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

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

CT: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. RC: Funding acquisition, Methodology, Supervision, Writing – review & editing, Conceptualization, Validation. LS: Funding acquisition, Methodology, Supervision, Writing – review & editing, Conceptualization, Validation.

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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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Enhancing adaptation to climate change by fostering collective action groups among smallholders in Punjab, Pakistan

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Climate change adaptation is increasingly recognized by subsistence farmers in Pakistan. The problem of climate change is severe, and smallholders are often resource constrained when it comes to adapting to it. However, such constraints can be overcome through collective responses. Therefore, it is necessary to evaluate the impact of collective action among smallholder farmers to determine how it influences local adaptation processes. This study explores the impact of farmer's collective action groups (CAGs) on adopting climate-smart agricultural (CSA) practices in poverty-stricken areas of rural Punjab, Pakistan. The data was collected through a cross-sectional survey, and for the analysis purpose, the Recursive bivariate probit regression (RBP) model was employed. The first stage estimates of RBP models suggest that the farmer's decision to participate in CAGs is mainly influenced by factors such as education, credit access, climate change risk perception, and peer influence. The second stage estimates showed a positive and significant impact of farmers' participation in collective action groups on adopting climate change adaptation strategies across all three models. The study concludes that the farmers participating in collective action groups have a higher climate change adaptation level. It is recommended that the pro-poor policies be designed to negate the entry barriers, facilitate the inclusion of the farmers in the collective action groups, and enhance climate change adaptation among smallholders.

KEYWORDS

collective action groups, climate change adaptation, recursive bivariate probit regression, Punjab, Pakistan

1. Introduction

Anthropogenetic emanations of greenhouse gasses are intensifying at an alarming rate, causing a destructive impact on ecological systems (The World Bank, 2017; Aryal et al., 2018; Arif et al., 2019). The damages are apparent around the globe; seemingly, the South Asian population is highly vulnerable to such climate extremes due to low adaptive capacity and mitigation awareness (Turner and Annamalai, 2012; Aryal et al., 2020). Recent climate change events, such as droughts, rising temperatures, floods, and consequent yield losses, have endangered the livelihoods of the rural class (Ricciardi et al., 2018; FAO, 2019). Estimations suggest that cereal yield may decline up to 30% by the year 2059 (Parry et al., 2007). The projections indicate that, by the next decade, South Asia will have the maximum number of food-insecure people (Cai et al., 2016; Hasegawa et al., 2021). Pakistan is considered the most vulnerable to the recent climate extremes, ranked 12th on the global climate index (Kreft et al., 2017).

Such catastrophic events need to be tackled via appropriate adaptation strategies. Climate-smart agricultural practices (CSA) follow holistic measures that help achieve socio-cultural, biophysical, and economic benefits from agriculture (Sanz et al., 2017; Awazi et al., 2021; Quandt et al., 2023). Adopting CSA is a viable option, as it can enhance crop production, increase farmers' revenue, and minimize environmental damage (Deressa et al., 2011; Tilman et al., 2011; Manda et al., 2016; Kotu et al., 2017; The World Bank, 2017; Awazi et al., 2019; Jayne et al., 2019). These integrated systems may include organic manure (Ebewore and Emaziye, 2016; Mahmood et al., 2017), integrated pest management (Pretty and Bharucha, 2015), soil and water conservation (Blanco and Lal, 2008), stress-tolerant crop varieties (Raymond Park et al., 2011), and crop management (Congreves et al., 2015; Ghani et al., 2022) among others. These measures enhance agriculture production and ensure economically feasible and socially acceptable usage of natural resources (FAO, 2022). According to Schwilch et al. (2014), institutions significantly influence land-use changes and adoption of sustainable measures. Further, Rasul et al. (2011) documented that institutions usually govern the processes by which technical and scientific knowledge is developed and translated into the application, as well as assist in adopting environmentally sustainable farming methods.

Existing literature has explored a range of institutional factors influencing the adoption of CSA technologies, such as agriculture advisory service (Salaisook et al., 2020), technology transfer (Kassie et al., 2015), market orientation (Ismail et al., 2023), and agriculture supporting services (Huber et al., 2013). However, only a scant portion of the literature discusses the role of collective action groups (CAGs). The empirical evidence focuses on the effectiveness of social groups in smoothing the adoption process through shared information and learning (Foster and Rosenzweig, 1995; Conley and Udry, 2010). Economic theory recommends that a wide range of human decisions, including the adaptation to climate change, are substantially related to the social behavior of groups to which farmers belong (Foster and Rosenzweig, 1995; de Janvry et al., 2017).

The failure to involve local communities in the policy framework has primarily resulted in the lack of climate change adaptation. Multiple studies indicate the effectiveness of local processes in synergy with national adaptation initiatives (Sanginga et al., 2006; Oparok, 2015; Chanie et al., 2017). Brown and Sonwa (2015) posited that interactions between local and national institutions can enhance the adaptation and effectiveness of the national policy. Osbahr et al. (2008) highlighted the adoption of collective land-use management as one of the local solutions to climate threats in Mozambique and recommended strengthening the local institutions. Adger (2010) and Mekonnen et al. (2016) suggested that collective action is crucial to adaptive capacity. This study prompted the need for case-specific research on the importance of collective action for adaptive capacity at the local level in rural agricultural communities.

Collective action groups (CAGs) consist of cooperatives, associations, communal action groups, self-help organizations, and producer organizations intended to protect members' interests. CAGs help farmers access necessary farming inputs and acquire credit and extension services. In other words, CAGs benefit farmers by enhancing their environmental stewardship and reducing global hunger in the face of climate uncertainties (Okumu and Muchapondwa, 2017). Such groups help in engendering a collective response to climate change threats at the micro and macro levels (Aldrich, 2010; Kehinde and Adeyemo, 2020). CAGs can vary in size and structure, ranging from small local cooperatives to larger associations or networks (Bizikova et al., 2020), and serve as valuable platforms for knowledge exchange, capacity building, resource access, and advocacy, all of which contribute to the widespread adoption of climate-smart agriculture technologies (Holloway et al., 2000; Hellin et al., 2009; Meinzen-Dick et al., 2009; Moustier et al., 2010; Trebbin, 2014).

The literature reports the diverse impacts of CAGs in promoting agricultural technologies. Thuo et al. (2014) found that farmer organizations have little effect on adopting improved ground varieties in Kenya and Uganda. Similarly, Mwaura (2014) confirmed that CAG members were less likely to adopt improved pesticides, seeds, and fertilizer in Rwanda. However, Zhang et al. (2023) found that participation in CAGs directly influenced farmers' choices to employ green control technologies among fruits and vegetable growers in China. Ainembabazi et al. (2017) suggested that CAGs significantly and positively affected farmers' adoption of pro-environment agricultural technology and technical efficiency in Africa's Great Lakes region.

The literature considering the relationship between CAGs and the adoption of agricultural technologies varies and is inconclusive. This variability may depend on the specific technology being adopted, access requirements, and the socio-economic profiles of the group members (Chanie et al., 2017; Abdul-Rahaman and Abdulai, 2018; Addai et al., 2021). Moreover, within the context of Pakistan, there is a shortage of literature assessing the effects of farmer-based groups. So far, only a few researchers have discussed the role of CAGs in Pakistan (Murray-Rust et al., 2001; Sabir et al., 2012; Gillani et al., 2022). However, these studies' analyses are primarily correlational, lacking causal inference.

Hence, it necessitates empirical research to determine the impact of farmers' collective action groups on adopting climate-smart agriculture technologies. To our knowledge, no prior study has explored the effects of participation in collective action groups on climate change adaptations, specifically in the South Asian context. Current research aims to fill this gap and adds to the existing literature by examining the relationship between farmers' decisions to join farmer-based collective groups and its effects on adopting CSA technologies in southern parts of Punjab, Pakistan. Both decisions (CAG membership and CSA adoption) are binary and incurred concurrently; hence, CAG membership is likely endogenous. To address the endogeneity and selection bias issues, this study employed the recursive bivariate probit model (RBP) to explore the objectives.

1.1. Conceptual linkage between collective action groups and climate change adaptations

Based on the empirical literature, the current study explains that the contextual factors largely determine farmers' decision to participate in collective action groups. Climate change has halted the progression of the farming sector and inversely affected the farmer's

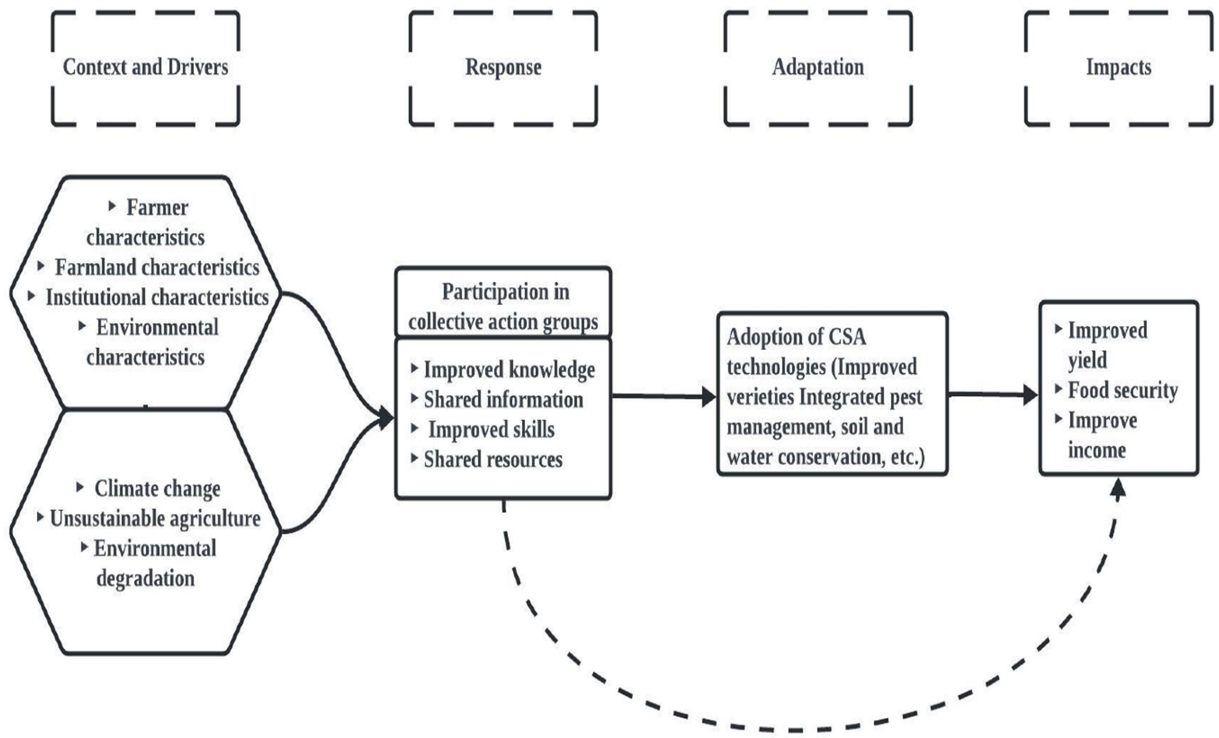

FIGURE 1
Conceptual framework.

livelihood. Hence, adaptation to climate change seems the only viable option to reverse the hazardous impacts of climate extremes. However, Climate-smart agricultural techniques are constrained by market imperfections, lack of awareness and financial resources (Mekonnen et al., 2018). Collective action groups are often described in numerous ways, specifically in the context of smallholder farming. It comprises several actors aiming toward shared purpose or interests among them (Meinzen-Dick et al., 2009; Fernández-Baldor et al., 2012). Collective action is primarily voluntary and takes different forms, such as making collaborative decisions, establishing standards of behavior and asset management, and putting policies into practice that directly affect communities in their daily lives (Ostrom, 2000). Other collective action activities involve pooling labor or financial resources or monitoring compliance with the guidelines.

A meta-analysis considering the adoption of soil management techniques emphasizes the positive role of information access in smoothing the way of adoption (Knowler and Bradshaw, 2007). Access to information can be gaged through group memberships (Lu et al., 2002; Mugonola et al., 2013; Kansiime et al., 2014). Membership in farming groups is crucial because it effectively disseminates information regarding new technologies and other activities related to market access. The empirical evidence shows the effectiveness of social networks in smoothing the adoption process through shared knowledge and learning from each other (Conley and Udry, 2010). A collection of networks (edges) between the cluster of individuals (nodes) signifies a network through which goods, services, and money flow (Maertens and Barrett, 2013). Collective groups facilitate interactions among the members, and decisions to adopt any agricultural innovation are influenced by shared experiences (Raymond Park et al., 2011). In the wake of natural disasters and low human index, multiple governments and non-governmental farmers' organizations (cooperatives, associations, producer organizations, etc.) are emerging in the region to improve farmers' well-being by connecting local communities and implementing integrative sustainable rural development. Adopting climate change adaptation techniques depends on farmers' perceptions of climate change and is primarily influenced by available information, socio-economic conditions, and agricultural operations (Kangalawe et al., 2017). Adoption is the extent to which farmers implement a new technology after receiving enough information about it and its potential benefits (see Figure 1).

2. Methodology

2.1. Study area and data collection

The study region is located in the southern parts (Figure 2) of Punjab, Pakistan. Such parts of the province are often vulnerable to climate catastrophes, such as floods, extreme temperatures, rainfall variations, and droughts; thus, most of the population suffers from poverty and malnutrition. Such parts carry the region's poorest, most vulnerable farming classes (Suleri and Iqbal, 2019; Jabbar et al., 2020a,b).

In the wake of natural disasters and low human index, multiple governments and non-governmental farmers' organizations are emerging in the region to improve farmers' well-being by connecting local communities and implementing integrative sustainable rural development. Numerous farmer-based groups exist in southern Punjab, Pakistan, such as cooperatives, associations, and producer organizations

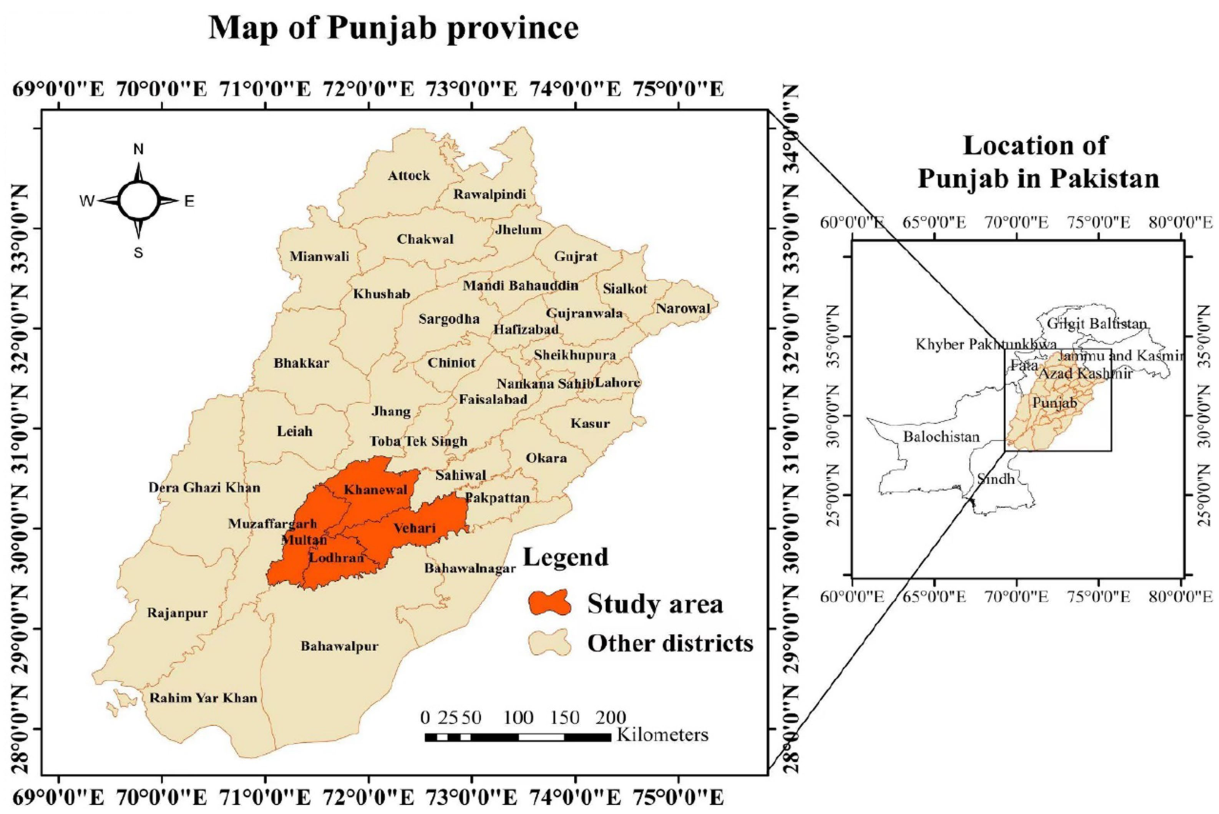

FIGURE 2
Location of the study area.

intended to protect members' interests. The study districts are homogenous in ecology and play a vital role in the country's agriculture.

$$n_0 = \frac{z^2 pq}{e^2} \frac{(1.64)^2 (0.5),(0.5)}{(0.04)^2} = 420 \quad (1)$$

Before data collection, a training session was conducted with a group of local university students for the enumeration purpose and all the guidelines concerning the data collection were communicated. We used a simple random sampling technique and a well-structured questionnaire to collect data. Based on the empirical evidence, we utilized the Cochran formula to determine the sample size of 420 (Equation 1) (Mukasa et al., 2020; Ojo and Baiyegunhi, 2020; Jabbar et al., 2020b; Myeki and Bahta, 2021). In the execution stage, verbal consent was obtained from the farmer at the start of an interview.

A prior stratification was not applied during the sampling procedure, ensuring equal chances of occurrences. At the first stage of data collection, the southern parts of Punjab province were purposively selected due to their agricultural contribution and the presence of collective action groups (Figure 3). In the second phase of data collection, four districts (Vehari, Khanewal, Multan, Lodhran) were chosen randomly. Sequentially, in the third phase, two sub-districts were further chosen. Subsequently, four union councils were selected from each of the sub-districts. In the fifth stage, five villages was selected from each union council. In the last step, 20 farmers from each village and 420 farmers were randomly selected in the fifth stage.

2.2. Data analysis

The data analysis for the existing study contains both descriptive and empirical research.

This study utilized the statistical package of Stata 14.0 for both the descriptive and empirical statistics. The descriptive analysis for this study explains the socio-economic characteristics of both the CAG members and non-members. The study utilized the recursive bivariate probit model to investigate the objectives. The RBP model seems a suitable option to examine the impact of binary endogenous treatment variables (Membership to collective action groups) on adopting binary outcomes (CSA technologies). RBP model is also helpful in controlling the observed and unobserved heterogeneities.

In comparison, the endogenous switching probit (ESP) model is also a sound econometric technique controlling for sample selection bias and endogeneity issues, but it lacks in estimating the marginal effects. Hence, given our interest in assessing the intensity and impact of the CAG membership on adopting CSA technologies, this study utilized the RBP model. It simultaneously estimates the choice of CAG membership and adoption of CSA technologies through the full information maximum likelihood (FIML) approach.

The following econometric framework explores the connection between farmers' decision to join CAGs and adopting CSA technologies (Abebaw and Haile, 2013; Ma et al., 2018).

$$y_1^* = \gamma Z' + \varepsilon, \text{ where } y_1 = 1 \text{ } if \text{ } y_1^* > 0, \text{ otherwise } y_1 = 0 \quad (2)$$

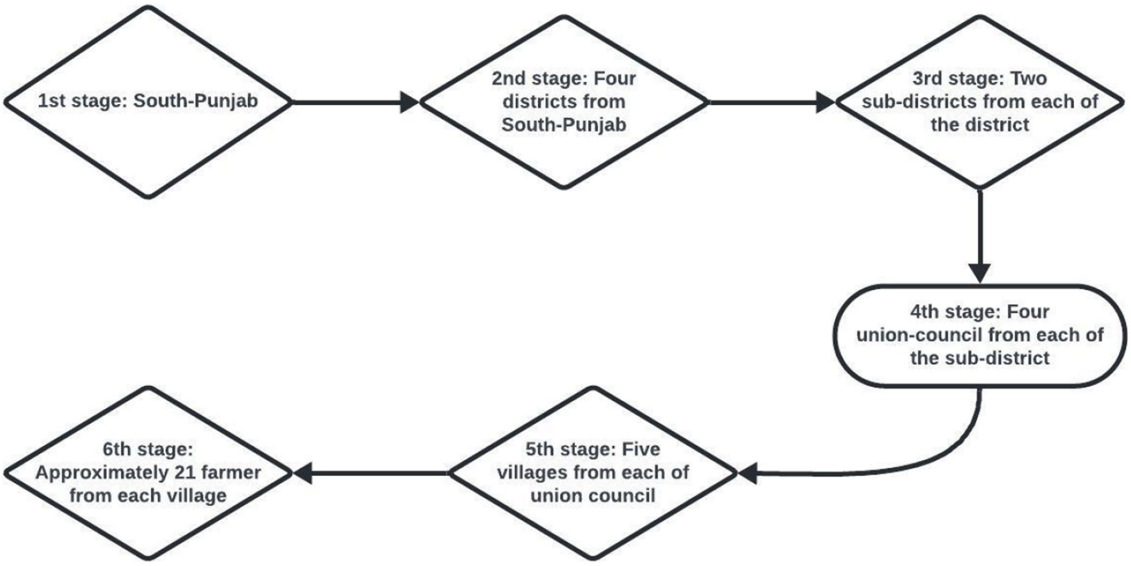

FIGURE 3
Sampling framework.

$$y_2^* = \varphi y_1^* + \lambda X' + \mu, \text{ where } y_2 = 1 \text{ if } y_2^* > 0, \text{ otherwise } y_2 = 0 \quad (3)$$

y_1^* is an unobserved latent variable reflecting group participation, similarly y_2^* Specifying the climate change adaptation. The y_1^* the variable displays endogeneity in the y_2^*. y_1 and y_2 signify the observable choices (0 or 1), where X and Z are vectors of covariates while λ and γ are vectors of unknown parameters to be projected. The terms μ and ε are residuals expected to be normally distributed, with a variance of 1 and zero mean and a correlation coefficient equal to ρ (Cameron and Trivedi, 2010). ρ specifies the association among the unobservable explanatory variables in three models. A full information maximum likelihood (FIML) was applied to counter endogeneity issues (Wooldridge, 2010). Likewise, Chang and Mishra (2008) mentioned four possible outcomes of RBP models, as discussed below.

(1) Farmer joins the group and adopts a CSA technology $(y_1 = 1, y_2 = 1)$
(2) Farmer joins group but does not adopt a CSA technology $(y_1 = 1, y_2 = 0)$
(3) Farmer does not join the group and adopt a CSA technology $(y_1 = 0, y_2 = 1)$
(4) Farmer does neither join the group nor adopt a CSA technology $(y_1 = 0, y_2 = 1)(y_1 = 0, y_2 = 0)$

2.3. Variable specification

This study intends to explore the impact of farmer-based groups on adopting climate change adaptation strategies. Hence, the treatment variable for farmers' group membership is a dummy where 1 = if the farmer is a CAG member and otherwise = 0. The food production system is challenging, interconnected, and heavily reliant on natural ecosystems. For developing economies, adaptation to the effects of climate change is crucial. In agricultural systems, intentional and accidental responses to climate vulnerability preserve ecological balance and reduce financial losses. Climate change and adaptation strategies should work in synergy to make it easier for the country to adapt to recent challenges. With farm, sectoral, and national policy backing, farm-level adaptation measures can reduce climate losses.

We selected three frequently applied CSA technologies, including climate-resilient improved verities (IV), soil and water conservation (SWC) techniques, and integrated pest management (IPM) by the smallholders in Punjab, Pakistan (Ali et al., 2015; Abid et al., 2016; Ali and Erenstein, 2017; Jabbar et al., 2020b). Improved verities are genetically modified cultivars to boost yield and resilience against diseases, insect pests, drought, parasitic weeds, and other environmental factors (Joshi et al., 2017). Soil and water conservation are local actions that maintain or improve the productive potential of the land, including soil, water, and vegetation, in places prone to degradation (Bashir et al., 2018). IPM is an ecosystem-based strategy that focuses on long-term pest or damage prevention using a combination of tactics such as biological management, habitat manipulation, and cultural practice modification (Heeb et al., 2019). All adaptation strategies were taken as the dummy variable where if the farmer adopts any climate change adaptation strategy = 1 otherwise = 0. We used current literature (Fischer and Qaim, 2012; Verhofstadt and Maertens, 2014; Mojo et al., 2017; Wossen et al., 2017) and anecdotal evidence to build the set of inputs or explanatory variables on what motivates farmers to join social groups. The following proxy variables could influence farmers' willingness to join CAGs. These include age, gender, education level, family size, land size, extension access, and peer influence (see Table 1 for definitions).

3. Results

3.1. Descriptive statistics

The membership status described in Table 1 reveals that approximately 63 of the sampled farmers were affiliated with non-government farmer development organizations in the study area. Additionally, around 51 and 48 of farmers were members of farming associations and cooperatives.

Table 2 shows the descriptive statistics reflecting an average year of schooling of 8, specifying that most farmers could read and write at an average age of 44 years; 75% percent of the respondents were males, and 57% were willing to take the risk. The average family size of 5.3 members per household. The average farm size was 3.24 acres, where 72% were owners. Around 62% of farmers were engaged in some off-farm activities. Among the institutional factors, nearly 48% of farmers had accessed credit, and 54% received an agricultural advisory recently. The average distance from the village to the main road was 3 kilometers. Peer influence is a crucial factor in stimulating the participation of farmer groups; peers' opinions influenced 58% of the participants. Nonetheless, it should be noted that the mean difference comparison may not consider other factors, which may compound the impact of CAG participation (Table 3).

3.2. Goodness of fit

We applied Murphy's score and Hosmer–Lemeshow tests to ensure the suitability of the RBP model. The findings showed that the p values are insignificant for both diagnostics mentioned above, suggesting the rejection of the Null hypothesis of normality and ensuring the suitability of the RBP model.

3.3. Recursive bivariate probit model

Table 4 presents RBP estimations for the determinants of CAGs membership and adopting CSA technologies. We also calculated the marginal effects for a better picture and meaningful results (Table 5). The Wald test for evaluating the null hypothesis that is statistically significant for all models suggests that the probability of farmers joining CAGs is indeed connected with their propensity to adopt CSA technologies. The rho across all three models significantly differs from

TABLE 1 Description of CAG members.

Membership status	No of CAG members
Member of farmer development organizations	63
Member of farmer associations	51
Member of agricultural cooperatives	48
Member of other self-managed farming groups	35
Total membership in collective action groups	197

TABLE 3 Goodness of fit measures for the RBP model.

	Hosmer–Lemeshow test	Murphy's score test
CAG membership and IPM adoption	chi2(9) = 11.52 Prob > chi2 = 0.2419	chi2(9) = 29.22 Prob > chi2 = 0.1089
CAG membership and SWC adoption	chi2(9) = 2.64 Prob > chi2 = 0.9767	chi2(9) = 12.57 Prob > chi2 = 0.9229
CAG membership and IV adoption	chi2(9) = 14.53 Prob > chi2 = 0.1048	chi2(9) = 17.95 Prob > chi2 = 0.6521

TABLE 2 Description and differences in characteristics of members and non-members statistics of the study.

Variable	Description	Mean	Non-members	Members	*T*-test
Integrated pest management (IPM)	Farmer adopt integrated pest management (1 = yes; 0 = no)	0.337	0.303	0.384	−1.773*
Improved verities (IV)	Farmer adopt improved verities (1 = yes; 0 = no)	0.357	0.311	0.423	−2.418**
Soil and water conservation (SWC)	Farmer adopt Soil and water conservation (1 = yes; 0 = no)	0.341	0.303	0.395	−2.009**
HH Age	Age number of years	44.756	44.614	44.956	−0.261
HH Education	Years of schooling	8.790	5.626	6.021	−9.185**
HH gender	Farmer is male (1 = yes; 0 = no)	0.753	0.754	0.752	0.050
Family size	Number of family members	5.380	5.015	5.895	−6.116
Risk attitude	Farmer is willing to take risk (1 = yes; 0 = no)	0.571	0.552	0.598	−0.966
ICT usage	Farmer is ICT user (1 = yes; 0 = no)	0.544	0.560	0.521	0.793
Farm ownership	Land owned in acres	3.216	3.322	3.065	0.512
Access to off-farm	Farmer is engaged in the off-farm activities (1 = yes; 0 = no)	0.620	0.636	0.696	1.331*
Credit access	Farmer has access to formal and non-formal credit services (1 = yes; 0 = no)	0.482	0.517	0.434	1.725*
Extension access	Access to extension services (1 = yes; 0 = no)	0.587	0.386	0.473	−4.169***
Risk perception of extreme temperature	Farmer perceive the risk extreme temperature (1 = yes; 0 = no)	0.722	0.739	0.697	0.955
Risk perception of rainfall variation	Farmers perceive the risk of rainfall variation (1 = yes; 0 = no)	0.548	0.490	0.631	−2.959**
Distance to the main road	Distance to the main road in kilometers	3.003	3.063	2.920	0.676
Peer influence	The nearest neighbor is an organizational member (1 = yes; 0 = no)	0.460	0.369	0.587	−4.618**

***, **, and * specify significance level at $p \leq 0.005$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

TABLE 4 The estimates of the RBP model for the impact of collective action groups on adopting climate smart agriculture practices.

	Model 1		Model 2		Model 3	
	CAG membership	IV	CAG membership	IPM	CAG membership	SWC
HH age	0.002 (0.005)	−0.001 (0.004)	0.003 (0.005)	0.003 (0.004)	0.003 (0.005)	0.003 (0.004)
HH gender	−0.024 (0.164)	0.204 (0.143)	−0.025 (0.166)	0.148 (0.144)	−0.014 (0.165)	0.164 (0.142)
HH size	0.033 (0.022)	0.008 (0.018)	0.027 (0.022)	0.012 (0.018)	0.024 (0.022)	0.012 (0.019)
HH education	1.161*** (0.134)	−0.278 (0.176)	1.151*** (0.133)	−0.291 (0.195)	1.151*** (0.134)	−0.340 (0.196)
Risk attitude	−0.078 (0.172)	0.154 (0.147)	−0.133 (0.179)	0.050 (0.154)	−0.151 (0.178)	0.034 (0.151)
ICT usage	0.099 (0.175)	0.059 (0.147)	0.170 (0.185)	0.336** (0.159)	0.191 (0.185)	0.306* (0.156)
Farm size	0.011 (0.014)	−0.002 (0.011)	0.014 (0.014)	0.001 (0.012)	0.015 (0.014)	0.001 (0.011)
Distance to main road	−0.036 (0.031)	−0.032 (0.029)	−0.038 (0.031)	−0.024 (0.029)	−0.038 (0.031)	−0.029 (0.029)
Access to off-farm	0.075 (0.194)	−0.439** (0.162)	0.051 (0.193)	−0.631*** (0.171)	0.051 (0.193)	−0.613*** (0.170)
Access to off-farm	0.075 (0.194)	−0.439** (0.162)	0.051 (0.193)	−0.631*** (0.171)	0.051 (0.193)	−0.613*** (0.170)
Risk perception of rainfall variation	−0.259 (0.164)	0.160 (0.142)	−0.262 (0.167)	0.127 (0.142)	−0.244 (0.132)	0.148 (0.140)
Risk perception of extreme temperature	0.377** (0.144)	0.011 (0.140)	0.361** (0.143)	0.024 (0.150)	0.369** (0.142)	−0.014 (0.146)
Credit access	−0.439** (0.144)	0.243* (0.130)	−0.423** (0.146)	0.168 (0.133)	−0.426** (0.145)	0.157 (0.132)
Extension access	0.310** (0.101)	0.141* (0.040)	0.121** (0.036)	0.108 (0.101)	0.226** (0.045)	0.119 (0.122)
CAG membership		1.234*** (0.385)		1.249** (0.433)		1.356*** (0.394)
Peer influence	0.458** (0.168)		0.449** (0.174)		0.391** (0.188)	
Constant	−6.946*** (0.862)	0.630 (0.950)	−6.877*** (0.858)	0.507 (1.064)	−6.882*** (0.865)	0.742 (1.042)
Rho ρ	−0.812* (0.420)		−0.967* (0.550)		−0.837 (0.211)	
Log-likelihood	−473.995***		−459.039		272.66***	
Wald x^2	193.79		252.75***		2.918*	
Wald test rho $\rho = 0$: x^2 (1)	3.7373*		3.082***			

***, **, and * specify significance level at $p \leq 0.005$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

zero, indicating the possibility of selection bias resulting from unobserved variables. The results in columns one, three and five showed that education, credit access, extension access, climate change risk perceptions, and peer influence significantly determined farmers' decisions to participate in collective action groups. The results considering the adoption of CSA technologies are presented in columns two, four, and six of Table 2. Findings highlighted the significant effects of ICT usage, off-farm participation, credit access, and CAGs membership on adopting CSA technologies.

4. Discussion

Based on the cross-sectional survey across the disaster-prone areas of the Punjab province, Pakistan, this study examines the impact of collective action groups in adopting climate-smart agricultural practices. The research utilized the recursive bivariate probit model to explore the objectives. The below section aligns the findings of this study with the empirical literature and intricate the policy implications.

4.1. Determinants of CAG membership

The years of educational attainment are positive and significantly related to farmers' decisions to participate in collective action groups. Education increases the farmer's awareness and ability to obtain necessary information considering farming decisions. Likewise, Chanie et al. (2017) confirmed a significant positive role of education in participating in farmers-based groups in Ethiopia. Similarly, Gurung and Choubey (2023) also reported a significant and positive relation between education and farmers decision to participate in farmer-based groups in India.

The scarcity of financial resources is one of the core reasons to participate in collective action groups (Gertler, 2004). Thus, farmer groups are likely to resolve financial constraints. This study reported significant mean differences among households having a credit source other than the farmer organization, suggesting that the probability of joining a CAG is less when the household has access to additional credit sources. Hence, the probability of accessing alternative financial resources influences the likelihood of joining a farmers-based organization. Accordingly, Nugusse et al. (2013) supported financial institutions' significant influence in determining farmers' decision to join agrarian groups.

Risk perception of extreme temperature is significantly and positively related to farmer-based groups' participation. Farmers with climate change risk perception are likelier to participate in farmers-based groups. Smallholders are often more vulnerable to climate extremities due to low adaptive capacity. Collective action groups mobilize the information and resources to address climate change threat (Ireland and Thomalla, 2011). Likewise, Ombogoh et al. (2018)

TABLE 5 Marginal effects of RBP model for the impact of collective action groups on adopting climate-smart agriculture practices.

	CAG membership	IV	CAG membership	IPM	CAG membership	SWC
HH age	0.001	0.001	0.000	−0.000	0.000	0.001
HH gender	−0.003	0.050	−0.006	0.066	−0.006	0.046
HH education	0.006	0.003	0.008	0.002	0.007	0.004
Family size	0.309	−0.105	0.308	−0.090	0.307	−0.091
ICT usage	0.051	0.095	0.026	0.019	0.045	0.105
Risk attitude	−0.040	0.010	−0.020	0.050	−0.035	0.015
Access to off-farm	0.013	−0.190	0.019	−0.142	0.013	−0.197
Farm ownership	0.004	0.000	0.003	−0.000	0.003	0.000
Distance to main road	−0.010	−0.009	−0.009	−0.010	−0.010	−0.007
Risk perception of rainfall variation	−0.065	0.046	−0.069	0.052	−0.070	0.039
Risk perception of extreme temperature	0.099	−0.004	0.100	0.003	0.096	0.007
Extension access	0.034	0.082	0.031	0.029	0.025	0.104
Credit access	−0.114	0.048	−0.116	0.079	−0.113	0.052
CAG membership		0.420		0.401		0.391
Peer influence	0.105		0.121		0.120	

and Ogunleye et al. (2021) support farmers-based groups' positive role in enhancing smallholders' adaptive capacity against climate variability.

Access to extension services is significantly and positively related to joining farmer-based organizations. Extension advisory communicates the benefits and persuades farmers to join farming associations. Circumstantially lacking information considering the farmer-based organization's benefits is a crucial reason for not joining CAGs (Thuo et al., 2014). Hence, access to information through governmental and non-governmental sources enhances the likelihood of joining CAGs. Accordingly, Nugussie (2010) suggests that recurrent extension visits increase farmers' awareness concerning the importance of farming organizations. Similarly, (Adi et al., 2021) found significant and positive impact of extension access and joining collective action groups among the Indonesian tobacco and sugarcane growers.

The association between peer influence and farmers' decisions to join agricultural organizations is significant and positive. Peer influence develops trust and willingness among households to join farmer groups and enjoy the same privileges as their peers. The findings also derive support from Ma and Abdulai (2016), who suggested the positive role of peers in stimulating the inclination toward joining agricultural organizations.

4.2. Determinants of adopting CSA technologies

Considering the usage of ICT, the results specify the significant and positive association between ICT usage and climate change adaptations, as the ICT users were 1.9 and 10% more likely to adopt IPM and SWC practices, respectively. The findings imply that endorsing ICT usage via a well-integrated approach by linking experts from different areas such as meteorology, crop protection, crop production, and input markets may broaden the ICT range. As suggested by Quandt et al. (2020) ICT should be a compulsory part in any government and non-government extension programs. Likewise, Ma and Wang (2020) reported a significant and positive relationship between ICT usage and the adoption of CSA technologies.

The coefficient of off-farm participation is significant and negative, indicating the inverse relationship between off-farm participation and adoption of CSA technologies. Off-farm work involves considerable labor, leaving little time to engage in on-farm activities. Besides, some farmers quit farming in the harsh climate and shifted to non-farm work. Ouma and Abdulai (2009) and Huang et al. (2019) also found that farmers with alternative sources of income are less likely to invest in sustainable agriculture practices. Contradictorily, Issahaku and Abdul-Rahaman (2019) reported a significant and positive impact of off-work in adopting soil and water conserving practices in the rain-fed areas of Ghana.

The findings indicated that farmers with credit access are 4,7, and 5% more likely to adopt improved verities, integrated pest management, and soil and water conservation practices. Credit arrangements are crucial in arranging the finance required for capital-intensive agricultural technologies. Likewise, Deressa et al. (2009) found a significant and positive relationship between credit access and climate change adaptation decisions in Nile basin of Ethiopia. Similarly, Olutumise (2023) also reported a significant and positive impact of credit access on adopting CSA technology among the smallholders of Nigeria.

Access to extension services is significantly and positively related with farmers decision to adoption improved verities. The extension advisory assists farmers in adopting a CSA technology and communicates its benefits. Circumstantially lacking information considering the CSA benefits is a crucial reason for not adoption. Hence, access to extension advisory enhances the probability of adopting CSA technologies. Similarly, Afroz and Akhtar (2017) found significant and positive impact of extension access and adoption CSA technologies among the Malaysian farmers.

Farmers' membership to collective action groups (CAGs) was significantly and positively related to the adoption of CSA technologies, as members were 42, 40, and 39% more likely to adopt improved verities, integrated pest management, and SWC practices, respectively. CAGs enable a collective environment that facilitates the optimization of shared resources such as funds, skills, knowledge, and labor. It improves farmers' adaptive capacity and awareness level, which ultimately promotes sustainable agriculture. Social contacts help disseminate information and increase awareness about agriculture technologies suitable for adaptation. Similarly, Awazi et al. (2019) stressed upon the importance of information access on farmers climate change adaptation decisions. Empirical evidence confirms the effectiveness of social networks in smoothing the adoption process of shared information and learning from each other (Foster and Rosenzweig, 1995; Conley and Udry, 2010). Likewise, Wossen et al. (2017) indicated that farmers with group membership were likelier to adopt the latest agricultural technologies than non-members. Further, in a review-based study, Bizikova et al. (2020) found that CAG members are more environmentally responsible and likely to adopt sustainable agricultural methods. Hence, policymakers should encourage social interactions among farmers, as peer influence can motivate others to join CAGs and embrace environment-friendly farming technologies (Ma, 2016).

4.3. Policy implications

This research provides useful, practical implications. It provides deep insights into the current literature on climate change adaptation, organic farming, and sustainable agriculture. A key finding of this study shows that CAGs contribute to the widespread adoption of CSA technologies in developing countries. It describes how the institutional role of CAGs manifests in adopting CSA technologies in developing countries. It advocates institutional transformation to promote and broaden climate-smart farming strategies. Hence, it is crucial to consider local institutional arrangements for collective action and governance processes to prepare for climate risks and adapt accordingly. Farmers can gain access to resources, skills, practices, and information due to improved governance processes within farmer groups. The creation of social safety nets and the application of risk reduction mechanisms can contribute to the reduction of vulnerability to climatic risks in the study sites. It is imperative to enhance technological skills and strengthen rural institutions' capacity to act collaboratively to facilitate adaptation. Thus, farmer groups must develop soft skills (critical thinking, problem solving, interpersonal, adaptability, etc.), as the capacity of governance processes and collective action for smallholder farmer groups depends on soft skills. To ensure access and benefit sharing, households must also learn how to mobilize and manage physical and financial assets. Though there is a strong presence of multiple government and non-government projects aiming to enhance climate change adaptation in the study area, smallholder farmers need to be recognized and involved in adaptation planning at the local level.

5. Conclusion

Climate change has affected every aspect of human life in the worst possible way. Developing countries continue to face devastations caused by climate change in the form of low crop yield, floods, food insecurity, and poverty. Lack of resources is considered the pertinent hindrance to climate change adaptation. To this end, smallholders in developing countries form groups to overcome resource and information constraints. Farmers' groups disseminate information about agricultural technologies and lessen the transaction cost to manage the risk associated with climate change. In this study, we examined the impacts of collective action groups on adopting CSA technologies among smallholders in rural Punjab, Pakistan. We employed the recursive bivariate probit model to explore the objectives. The first stage probit estimates of the RBP model showed that the decision to join CAGs is primarily determined by non-farm participation, credit access, extension access, and peer influence. The second stage estimates of the RBP model showed that CAG members are more likely to adopt CSA technologies.

Notably, extension access and peer influence positively influence the farmers' decision to join the CAGs. The findings call for strengthening the extension system at the governmental and non-governmental levels to encourage the formation of CAGs. Relevant agencies should pay attention to spreading awareness, advancement of institutional coverage, and rural infrastructures to stimulate the rural public in forming social networks, thus solving socio-economic and food security issues. In designing policies to encourage the voluntary adoption of CSA technologies, it is imperative to consider the importance of social interactions among farmers. Policymakers should specifically consider supporting collective group initiatives, where farmers can exchange information and share their farming experiences with fellow group members.

Further, policymakers should ensure that CAGs access better seeds, farming inputs, organic fertilizer, and integrated pest management equipment, which can be better achieved through public–private partnerships. The pro-poor policies must be designed to eliminate entry barriers and facilitate inclusion in the farmers' group activities. Future research may consider the influence of social norms and beliefs on smallholders' climate change adaptation decisions and group participation decisions.

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

AJ: conceptualization, data analysis, data description, explanation of results, and writing. WL and JL: data analysis and writing. YW and JP: conceptualization, methodology, explanation of results, reviewing, and editing. JZ and QW: conceptualization, explanation of results, reviewing, and editing. 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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Flood-tolerant rice for enhanced production and livelihood of smallholder farmers of Africa

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Climate change has intensified food security challenges, especially in Africa, where a significant portion of produce is reliant on smallholder farmers in rainfed conditions. Prolonged flooding and droughts, driven by erratic weather patterns, have significantly elevated the risk of food scarcity. Floods, in particular, have been responsible for severe crop losses, raising concerns about increasing import costs if this issue is not mitigated. Africa is actively working to mitigate the impacts of flooding and enhance food security, although progress has been gradual. Developing flood-resilient varieties is a promising strategy to address this challenge. We explored various flood types common in the region and observed a scarcity of research on flood-resilient varieties, particularly those adapted for anaerobic germination and stagnant flooding. Conversely, varieties bred for flash flooding, such as FARO 66 and FARO 67, have seen limited distribution, primarily confined to a few West African countries, falling short of the intended impact. In contrast, deepwater tolerance research dates back to the early 1900s, but commercialization of the varieties remains limited, with scarce information regarding their cultivation, coverage, and performance. Newly developed varieties, such as Kolondieba 2 and Kadia 24, have received less attention, leaving many farmers dependent on locally adapted cultivars specific to particular areas. Remarkably, despite the limited information, both released and local stress-tolerant cultivars exhibit substantial survival rates and yield advantages. For instance, FARO 66 and FARO 67 have demonstrated 1–3 t/ha yield advantages over recurrent parents under flooding stress. Nonetheless, further efforts are required to address various forms of flooding. To this end, AfricaRice collaborates with National Rice Development Strategies, IRRI, and other partners to promote research and development. While improved flood-tolerant varieties remain limited in scope across Africa, the financial gains for farmers are significant when compared to susceptible cultivars. As the continent's population continues to grow rapidly, there is untapped potential in African germplasms, making ongoing research and breeding strategies essential. Therefore, this review highlights the importance of intensifying efforts in screening and identifying flood-tolerant rice. Furthermore, it underscores the value of utilizing traditional flood-resilient cultivars in breeding to enhance the productivity of widely distributed and cultivated varieties.

KEYWORDS

climate change, floods, smallholder farmers, rainfed conditions, flood-tolerant varieties

1 Introduction

Rice serves as a dietary cornerstone for over half of the world's population (Muthayya et al., 2014). It contributes significantly, accounting for approximately 23% of the daily caloric intake (Chemutai et al., 2016). Asia has historically dominated rice production, with China and India jointly responsible for over 90% of the world's rice output (Fukagawa and Ziska, 2019). Nevertheless, substantial changes have been observed in Africa, driven by shifts in dietary preferences, population growth, and urbanization. Tsujimoto et al. (2019) highlight a significant surge in rice consumption, from 9.2 Mt. in 1990 to 31.5 Mt. in 2019. This rapid growth in consumption is beginning to strain production capacities. Ibrahim et al. (2022) reported that between 2009 and 2019, Sub-Saharan Africa's (SSA) average rice consumption stood at 27.4 Mt., surpassing the average production of 15.4 Mt. over the same period.

This persistent deficit between production and consumption has made Africa heavily reliant on rice imports, incurring substantial costs [Africa Rice Center (AfricaRice), 2011]. Over the past five decades, Africa has experienced a notable increase in rice production, primarily attributed to the expansion of cultivated areas rather than substantial improvements in productivity (FAOSTAT, 2012). Africa's average rice yield lags significantly behind that of Asia, with African farmers harvesting an average of 2.28 tonnes per hectare (t/ha) compared to Asia's 4.61 t/ha (Arouna et al., 2021). This productivity gap is particularly pronounced among small-scale resource-poor farmers who practice rainfed agriculture (Hong et al., 2021). Africa Rice Center (AfricaRice) (2011) asserts that addressing these constraints is essential to curb rice import dependence, which can be achieved through research and development efforts.

Some of the major challenges for rice farmers across Africa are flooding and prolonged dry spells. These challenges have become more frequently pronounced as the largest African production areas are located in rainfed environments that suffer from weather variabilities [Diagne et al., 2013b; Africa Rice Center (AfricaRice), 2019]. These abiotic constraints interact with harsh weather conditions, amplifying their detrimental effects. Recent data from Hong et al. (2021) emphasize that small-scale farmers are responsible for more than 90% of rice output in Africa. Rainfed farming dominates rice production in most Sub-Saharan African countries (Dramé et al., 2013), with nearly 70% of rice production occurring under rainfed conditions (Ibrahim et al., 2022). Rainfed lowlands, in particular, contribute significantly to rice production in Africa, encompassing approximately 37% of cultivated areas and yielding 48% of the production [Africa Rice Center (AfricaRice), 2011].

However, the full potential of rainfed lowlands remains untapped due to challenges related to the adverse effects of floods (Agbeleye et al., 2019). It is evident that African major rice-growing areas are flood prone (Kuya et al., 2019), with varying water levels, crop stages during floodwater occurrence, and durations of water accumulation. Moreover, with the existence of various ecosystem types, even the types of flooding are different; some areas experience more than one type. These types commonly include floods at germination, flash floods, partial submergence, and prolonged deep water (Agbeleye et al., 2019). It is devastating that the impacts of flooding are capable of causing total crop losses, thus leading to famine. Therefore, addressing the challenges posed by floods is imperative to enhance rice productivity and expand rice cultivation areas, particularly in rainfed lowlands.

Developing high-yielding, flood-tolerant rice is essential for ensuring resilience in rice farming (Bairagi et al., 2021). While extensive research has been conducted globally, there is limited and scattered research specific to Africa. Mackill et al. (2012) have reported the promising adoption of flood-tolerant varieties by the majority of farmers in Asia. However, this is not the case for Africa, where there are few reports regarding the adoption, distribution, and use of varieties capable of withstanding inundation. The intriguing scenario is that the continent possesses a wealth of rice cultivars suitable for genetic improvement. This offers promise for breeding efforts in the face of escalating weather challenges. Therefore, to potentially harness the rice-growing areas where floods are common, it is imperative to publicly reveal the current measures and future directions for developing flood-tolerant rice. As a result, this review aims to present Africa's current progress in addressing the various types of flooding stresses in rice cultivation.

2 Overview of rice sector in Africa

2.1 Rice area and productivity

Rice plays a vital role in ensuring food availability and income security for both rural and urban populations in Africa. Smallholder farmers are at the forefront of rice production, with more than 80% of the total production in Africa attributed to them (Sie et al., 2012; Tanaka et al., 2017). The expansion of rice cultivation has shown varying trends over the years, and it is evident that the increase in production is primarily linked to the expansion of cultivation areas. Balasubramanian et al. (2007) pointed out that there is an immense potential for rice cultivation in Africa, with approximately 239 million hectares of potential wetlands available. However, it is unfortunate that less than 5% of this land is currently utilized for rice cultivation. A report by the FAO in 2008, cited by Rodenburg and Johnson (2009), indicated a significant 105% increase in harvested rice area over three decades, which was driven by the growing demand for rice.

According to Africa Rice Center (AfricaRice) (2011), the total area utilized for rice production in Africa was around 10 million hectares, encompassing all African countries engaged in rice cultivation. Nigatu et al. (2017) highlighted that in 2016, the harvested rice area in Sub-Saharan Africa reached 11.2 million hectares, representing a 4.2% increase between 2010 and 2016. However, the notable increase in production was primarily attributed to the expansion of cultivation areas rather than improvements in yield per hectare. In 2010, rice productivity in Africa was reported to be 2.1 t/ha, and this yield remained relatively consistent between 2014 and 2016 (Nigatu et al., 2017). Other studies by Roy-Macauley (2018) and Tsujimoto et al. (2019) reported similar rice yields in the range of 2.1 to 2.35 t/ha for Sub-Saharan Africa. A more recent study by Arouna et al. (2021) estimated the average rice yield in Africa to be 2.28 t/ha, while Rodenburg and Saito (2022) indicated that Africa's rice yield is around 2 t/ha.

Comparing these yield figures to the potential yield gap of 2–10 t/ha reveals that Africa is currently achieving only a fraction of its rice production potential. Addressing the constraints that limit production is crucial for improving the supply of rice in Africa and closing this yield gap.

2.2 Major producers

The trends in rice production in Africa reveal a general increase in production, although this increase has not kept pace with the growing demand for rice. Longtau (2003) highlighted that West Africa, in particular, had the highest production and consumption of rice in Africa, accounting for 64.2% of production and 61.9% of consumption. Notable rice-producing countries in Sub-Saharan Africa (SSA) identified by Rodenburg and Johnson (2009) include Nigeria, Madagascar, Guinea, Sierra Leone, Egypt, the Democratic Republic of Congo, Mali, Côte d'Ivoire, Tanzania, and Mozambique. Mutiga et al. (2021) and Nigatu et al. (2017) noted that nearly 80% of rice production and consumption in SSA can be attributed to Nigeria, Madagascar, Côte d'Ivoire, Tanzania, Mali, Guinea, Sierra Leone, and Senegal.

Recent data from FAOSTAT (2023), which provides information on harvested rice area and production, confirm that West Africa has the largest harvested rice area and highest actual production among the five African regions (Table 1). In contrast, Southern Africa recorded the lowest rice area and production. Nigeria stands out as the leading rice producer in Africa, surpassing all other countries by a significant margin. In 2020, Nigeria's rice production reached 8.17 Mt., making it the largest producer on the continent. Egypt, Madagascar, Tanzania, and Mali also feature among the top rice-producing countries (Table 2). While some countries experienced a decline in rice production between 2010 and 2015, such as Madagascar, Tanzania, and Sierra Leone, most of Africa's major rice-producing nations saw an increase in production during this period. From 2015 to 2020, only Côte d'Ivoire and Egypt reported a reduction in rice production among the ten selected major rice producers in Africa.

Overall, the upward trend in rice production in recent years is primarily attributed to the expansion of rice cultivation areas, the introduction of rice varieties with desirable cooking traits and reduced shattering, productive research efforts such as the development of NERICA varieties, the involvement of farmers in varietal development, and increased awareness of good agricultural practices (Mogga et al., 2018; Arouna et al., 2021; Bin Rahman and Zhang, 2022).

2.3 Rice ecosystems

Africa's rice ecosystems are diverse and vary across countries, with differing representations and proportions. Balasubramanian et al. (2007) categorized rice ecosystems in Africa into five groups: deep water and mangroves (9%), rainfed upland (38%), rainfed lowland (33%), and irrigated (20%). However, there have been slight variations in these proportions reported by different sources. Rodenburg and Johnson (2009) revised these figures with a slightly different distribution, reporting rainfed upland (39%), rainfed lowland (33%), and irrigated (19%), while deep water and mangroves covered only 9%. The presence of deep water and mangroves was noted in the flood plains of the Niger River, covering countries such as Guinea, Mali, and Nigeria, while coastal areas of Sierra Leone, Liberia, and Gambia had mangrove ecosystems.

Several other sources, including Africa Rice Center (AfricaRice) (2010), Sakagami and Kawano (2011), Sie et al. (2012), Diagne et al. (2013a), and Suvi et al. (2020), have reported similar rice ecosystems with minor variations in the distribution percentages. Despite these minor differences, the general trend remains consistent, with rainfed upland being the largest ecosystem, followed by rainfed lowland and irrigated. According to Africa Rice Center (AfricaRice) (2010), only 14% of the rice ecosystem is irrigated, while rainfed upland and lowland account for 40 and 37%, respectively. The distribution of these ecosystems can change over time due to shifts in land utilization patterns. Diagne et al. (2013a) reported a total rice cultivation area of 9.9 million hectares, with rainfed lowland (38%) being the most extensive ecosystem, followed by rainfed upland (32%) and irrigated (26%). In contrast, deep water and mangroves had the smallest share of rice cultivation area, with only 4% coverage. Generally, the distribution of rice ecosystems in Africa aligns with the findings of Diagne et al. (2013a) and Africa Rice Center (AfricaRice) (2019), which indicate that more than 70% of the rice area in Sub-Saharan Africa is rainfed. Among these ecosystems, rainfed upland, rainfed lowland, and irrigated are the most widespread and dominant (Diagne et al., 2013a; Rodenburg and Saito, 2022).

TABLE 1 Rice harvested area and production by African zones from 2010 to 2020 as per FAOSTAT Database (https://www.fao.org/faostat/en/#data/QCL; accessed February 20, 2023).

Zone	Year					
	2010		2015		2020	
	Harvested area (Mha)	Production (Mt)	Harvested area (Mha)	Production (Mt)	Harvested area (Mha)	Production (Mt)
Eastern Africa	2.9616*	8.3853[a]	2.8858[a]	6.6055[a]	3.4479*	8.6531[a]
Middle Africa	1.3194*	1.1537[a]	1.7855*	1.6019[a]	1.8053*	2.1207*
Northern Africa	0.4735[a]	4.4036[a]	0.5269[a]	4.9135[a]	0.517[a]	4.9041[a]
Southern Africa	0.0013*	0.0037*	0.0014*	0.0039*	0.0014*	0,0041*
Western Africa	6.5121[a]	12.0591[a]	8.3207*	17.6577[a]	9.5692*	20.5195[a]
Grand Total	11.2679	26.0054	13.5203	30.7825	15.3408	36.2015

The asterisk (*) indicates the estimated value, while superscript ([a]) indicates actual value. Total area and harvests were termed as grand total since they are a summation of some actual and estimated values.

TABLE 2 Rice production statistics from 2010 to 2020 among the ten highest rice producers in Africa (FAOSTAT Database, https://www.fao.org/faostat/en/#data/QCL; accessed February 20, 2023).

Country	Production (Mt)		
	2010	2015	2020
Nigeria	4.4725	7.1866	8.1718
Egypt	4.3295	4.8179	4.804
Madagascar	4.7379	3.7223	4.2279
Tanzania	2.6501	1.937	3.038
Mali	1.2961	2.3311	3.01
Guinea	1.6137	2.0474	2.459
Côte d'Ivoire	1.2061	2.153	1.4812
Senegal	0.6040	0.9063	1.3497
Sierra Leone	1.0267	0.8717	1.0498
Ghana	0.4916	0.6415	0.9869

When it comes to rice production contribution, Africa Rice Center (AfricaRice) (2011) reported rainfed lowland as the largest contributor, accounting for 48% of total production, followed by irrigated (33%) and rainfed upland (19%). Productivity levels also vary among these ecosystems, with irrigated rice typically achieving higher yields compared to rainfed systems. According to Ibrahim et al. (2022), the average rice yield in Sub-Saharan Africa is around 2 t/ha, while well-utilized rainfed and irrigated systems can produce 4–9 t/ha and 8–11 t/ha, respectively. Africa Rice Center (AfricaRice) (2011) reported average yields of 1 t/ha for upland, 1–3 t/ha for lowland, and 3–6 t/ha for irrigated rice. However, these yields are still below the potential yields for each ecosystem, which are 2–4 t/ha, 3–6 t/ha, and 6–15 t/ha, respectively. Recent data published by Saito et al. (2019) indicated actual yields of 1.6 t/ha for rainfed upland, 2.6 t/ha for rainfed lowland, and 3.9 t/ha for irrigated rice. These values, while improved, still fall short of the ecosystems' full potential yields.

2.4 Overall production, consumption, and imports

Over the years, there has been a persistent gap between rice production and demand in Africa. From 1961 to 2005, rice production grew at a rate of 3.23%, while demand outpaced it, increasing at a rate of 4.52% (Sie et al., 2012). Africa Rice Center (AfricaRice) (2011) also noted this trend and reported a deficit of 9.68 Mt. of milled rice, resulting in a cost of 5 billion USD for imports. This deficit persisted as the average rate of increase in rice production from 1970 to 2009 (3.3%) lagged behind the rate of consumption growth (4.0%). In recent years, there have been notable increases in rice production. For instance, in 2009, Seck et al. (2010) reported a production of 16 Mt. of milled rice, a significant milestone compared to the mere 2 Mt. produced in Sub-Saharan African countries in 1961. Zenna et al. (2017) compared rice production trends from 1992 to 2002 and 2003 to 2013, revealing an increase of 2 and 4%, respectively. This increase was attributed to the expansion of production areas, the use of improved varieties, and the adoption of modern agricultural inputs. Despite these production gains, rice imports have continued to rise. In 1961, only 0.5 Mt. of rice was imported into Africa from outside the continent (Seck et al., 2010). By 2003, this had grown to an imported rice cost of 1.5 billion USD (Balasubramanian et al., 2007). More recent statistics have also shown an increase in rice imports, primarily due to the rising consumption of rice among African nations (Rodenburg and Saito, 2022).

According to the FAO statistics for Crops and Livestock Products in 2023, total rice production in Africa reached 36.2 Mt. in 2020, up from 26 Mt. in 2010 and 30.8 Mt. in 2015. Despite this increase in production, rice imports have continued to grow. The annual report for 2016 by Africa Rice Center (AfricaRice) (2017) indicated that demand for rice in some African countries ranged from 10 to 90%, leading to an annual import cost of 5.5 billion USD to meet requirements. The consumption of rice in Africa has been on the rise. Tsujimoto et al. (2019) observed a significant increase in rice consumption from 9.2 Mt. in 1990 to 31.5 Mt. in 2019. In 2018, Africa spent almost 6 billion USD on importing nearly 25% of its rice for consumption. The average annual rice consumption from 2009 to 2019 was reported to be 27.4 Mt., while production lagged at only 15.4 Mt. (Ibrahim et al., 2022). Rodenburg and Saito (2022) noted that African rice imports accounted for almost 40% of the rice consumed, with the primary driver being the increasing demand for rice.

Projections for the future suggest that rice consumption will continue to rise. The FAO (2023b) projects a further increase in consumption to reach 34.9 Mt. in 2025. Nigatu et al. (2017) have also highlighted the risk of importing more rice, projecting an increase from 27 to 35 Mt. in 2026 if corrective measures are not implemented. These trends underscore the urgency of addressing the gap between rice production and consumption in Africa.

3 Rice production challenges and opportunities in Africa

3.1 Challenges

Diagne et al. (2013b) have categorized the challenges facing African rice farmers into various categories, including biotic, soil-related, and climate-induced factors. Africa Rice Center (AfricaRice) (2011) emphasizes that these factors are further exacerbated by socio-economic constraints. These challenges encompass a wide range, such as iron toxicity, droughts, floods, cold salinity, weed infestations, diseases, birds and rodent pests, suboptimal seed quality, impoverished soils, and inadequate post-harvest technologies (Balasubramanian et al., 2007; Rodenburg and Johnson, 2009; Diagne et al., 2013b; Van Oort, 2018; Hong et al., 2021).

The primary focus of this review is on flooding, a major challenge in both rainfed lowlands and irrigated areas. It is often triggered by unpredictable rains associated with climate change (Agbeleye et al., 2019). Farmers have recognized this stress, which ranks second only to drought in terms of its impact, accounting for a 27% yield loss across all ecological zones (Diagne et al., 2013b). The impacts of flooding are observed throughout lowland rice-growing areas, and in particularly stressful years, farmers experience total crop failure. This challenge manifests in various forms, affecting different stages of the rice production cycle, from sowing to harvest. Flooding affects germination, tillering, plant survival, lodging, spikelet fertility, grain weights, and ultimately yields. It also hinders the recovery of most rice cultivars (Panda and Barik, 2021).

In addition to flooding, other challenges significantly impact rice production in Africa. Drought, for instance, is a devastating impediment to rice production for African farmers. It resulted in a yield loss of 29% during the 2009–2010 period across all rice ecosystems, with upland rice being particularly susceptible (Diagne et al., 2013b). Moreover, weeds have consistently emerged as one of the most formidable biotic challenges, especially in rainfed rice farming, where yields can be less than 1 ton per hectare [Rodenburg and Johnson, 2009; Africa Rice Center (AfricaRice), 2011]. Parasitic weeds, including the Striga genus, inflict substantial monetary losses, estimated to range between 111 million and 200 million USD annually [Rodenburg and Johnson, 2009; Africa Rice Center (AfricaRice), 2017]. Other pests such as the African rice gall midge, birds, and rodents also pose significant threats to rice production. Furthermore, rice in Africa faces diseases such as bacterial leaf blight, Rice yellow mottle virus, and blast. Bacterial blight, for instance, inflicted yield losses ranging from 35 to 52% in Niger and 25% in the northern part of Benin [Africa Rice Center (AfricaRice), 2011; Suvi et al., 2020].

Mineral toxicity, particularly iron toxicity, has afflicted numerous African countries, leading to yield losses ranging from 10% to a staggering 100% (Melandri et al., 2021). West African nations have borne the brunt of the iron toxicity challenge, with nearly 60% of their cultivated areas affected (Sikirou et al., 2018). Likewise, the detrimental impact of excessive aluminium on rice crops has become increasingly apparent, affecting approximately 18.8% of rice-growing regions in Africa. Besides the biotic and abiotic challenges, the financial constraints and limited awareness among smallholder farmers pose significant barriers to their access to improved agricultural inputs and technologies. In addition to these challenges, many African soils suffer from nutrient deficiencies, particularly in nitrogen (N), phosphorus (P), potassium (K), and zinc (Zn) (Mohammed et al., 2014; Tsujimoto et al., 2019; Hong et al., 2021). It was found that more than 37.6% of rice-growing areas in Africa grapple with low soil nutrient levels, leading to reduced crop yields (Haefele et al., 2014). Furthermore, access to quality seeds and varieties represents another major challenge to sustainable rice farming in Africa, as highlighted in the Africa Rice Center's annual report of 2010. Similarly, Futakuchi and Saito (2021) observed farmers' overreliance on saved seeds for crop cultivation.

Finally, the post-harvest phase of rice production experiences losses in value, ranging between 15 and 50% (Somado et al., 2008). These losses result from suboptimal post-harvest practices, including the presence of impurities, chalkiness, heat damage, and a high quantity of broken rice [Africa Rice Center (AfricaRice), 2016]. Sub-Saharan Africa experiences post-harvest losses ranging from 9 to 17%, amounting to an estimated 14–600 million USD in losses each year [Africa Rice Center (AfricaRice), 2018]. Therefore, addressing these challenges is paramount for enhancing both the quality and quantity of rice production and, subsequently, improving overall food security in the region.

3.2 Unlocking Africa's future potential for rice self-sufficiency

Africa's rice production landscape stands as a realm of untapped potential, awaiting realization through a dedicated embrace of research and development endeavors aimed at fostering sustainable rice farming practices [Africa Rice Center (AfricaRice), 2011]. The age of heavy rice imports, which has placed undue pressure on Africa's economic resources, must give way to a future where the continent takes charge of meeting its own rice demands. The sluggish pace of rice production growth in Africa, attributed to the underutilization of available arable land and persistently low productivity levels, calls for a strategic transformation (Ragasa and Chapoto, 2017; Rodenburg and Saito, 2022). Africa possesses the intrinsic potential to attain self-sufficiency once it commits to strategies that optimize land utilization and enhance overall productivity (Arouna et al., 2021).

Remarkably, Africa boasts vast expanses of land amenable to rice cultivation, yet only a fraction of its fertile wetlands currently witness the plow [Africa Rice Center (AfricaRice), 2011]. Astonishingly, out of the over 200 million hectares of wetlands spanning the African continent, a mere 5% find themselves under the cultivation of rice. It is this very underutilized land that, when accessed and cultivated, holds the power to significantly augment rice production. Furthermore, addressing the gap in the availability and accessibility of high-yielding rice varieties represents a pivotal opportunity for productivity enhancement [Africa Rice Center (AfricaRice), 2010]. Across the continent, farmers are predominantly cultivating traditional local rice varieties, relying on saved seeds year after year [Africa Rice Center (AfricaRice), 2012]. Yet beneath this challenge lies a wealth of diverse cultivars that remain ripe for improvement. Agricultural research institutions have been established in numerous countries, many with a particular focus on rice breeding. These initiatives promise to equip African farmers with superior quality and high-yielding rice varieties, consequently leading to an upsurge in output. Moreover, the rising demand for rice varieties tailored to withstand a gamut of stressors, from floods to prolonged dry spells, salinity, and nutrient imbalances, presents a compelling impetus for progress (Balasubramanian et al., 2007). The introduction of stress-tolerant rice varieties signifies more than just an expansion of cultivated land; it holds the promise of significantly enhancing productivity. Going beyond the NERICAs, the Africa Rice Center has successfully developed Sahel, ARICAs, and WITAs high-yielding varieties that are finely tuned to suit various African ecologies and withstand prevalent stresses. These varieties have the potential to bolster the livelihoods and incomes of smallholder farmers (Arouna et al., 2017). By making strategic investments in this endeavor, the continent stands poised to breathe new life into long-abandoned agricultural lands, ultimately resulting in a substantial increase in rice production.

To facilitate the rice transformative journey, the implementation of supportive agricultural policies takes center stage (FAO, 2023a). These policies wield the power to steer the trajectory of the rice sector's development (Clapp, 2017). They are inextricably linked to initiatives such as mechanization, the subsidization of agricultural inputs, and the provision of accessible loans to farmers (Arouna et al., 2021). These measures collectively ensure the efficient organization of farming activities, the timely application of agronomic practices, and the seamless management of the post-harvest value chain. In addition, these policies are aligning with the national rice development strategies (NRDS), which are now being implemented by the majority of African countries. Therefore, Africa stands at the cusp of a remarkable transformation, one that holds the promise of self-sufficiency in rice production. By harnessing its abundant resources, embracing research and development, and fortifying the supportive policy landscape, the continent is poised to unlock its full potential and emerge as a beacon of sustainable rice farming.

4 Flooding and rice production in Africa

4.1 Weather variability and prevalence of floods

Flooding limits rice production, particularly in rainfed lowland ecosystems. This is exacerbated by the irregular and uncertain distribution of rainfall, in itself accelerated by climate change, which is a major concern today (Mackay, 2008). Weather variability has increased globally, and Africa's heavy reliance on rainfed agriculture makes it highly vulnerable to weather extremes, including floods (Agbeleye et al., 2019). Projections for the future suggest an escalation in the frequency and intensity of weather extremes due to climate change [Atanga and Tankpa, 2021; World Meteorological Organization (WMO), 2022]. A report by the UN Office for the Coordination of Humanitarian Affairs (OCHA, 2022) identified 19 countries prone to floods with significant damage to farmlands. These countries include Chad, the Democratic Republic of Congo, Niger, Nigeria, Liberia, the Central African Republic, Gambia, Guinea, Mauritania, Senegal, Côte d'Ivoire, Ghana, Sierra Leone, Mali, Cameroon, Benin, and Burkina Faso. In 2021, approximately 15 African nations also experienced flooding. Akinyoade et al. (2014) conducted surveys in countries such as Kenya, Ethiopia, and Mozambique. The results revealed that more than 90% of respondents perceived the existence of floods and droughts as a major threat to crops.

Several countries such as Tanzania have a history of riverine flooding, especially in floodplains, which significantly affects overall agricultural productivity (Valimba and Mahe, 2020). Other countries, including Nigeria, Madagascar, Mali, Sierra Leone, Uganda, Burkina Faso, and Rwanda, have reported flood-related disruptions to agriculture in certain years [Africa Rice Center (AfricaRice), 2011, 2018; Anna et al., 2019]. The World Meteorological Organization (WMO) (2022) projected an increase in the severeness of climate extremes. Hence, the organization estimated that Africa will need to spend nearly $50 billion USD annually by 2050 to mitigate these weather-related losses. Therefore, addressing the challenges posed by flooding in rice production can never be neglected in Africa.

4.2 Types of flooding in rice

Ismail et al. (2012) identified four inundation stresses that rice farmers are likely to encounter: flooding at germination, flash flooding, long-term partial flooding, and deep water. They further distinguished these stresses, highlighting anaerobic germination, which encompasses submergence stress during germination caused by heavy rains occurring shortly after sowing. This phenomenon is prevalent among farmers who practice direct seeding. Flash floods are another perilous event that submerges crops for a short duration, typically one to two weeks, resulting in crop damage or death. This is distinct from long-term stagnant flooding, where water levels of 30–50 cm accumulate for a significant portion of the growing season. Stagnant flooding is sometimes referred to as partial flooding. Additionally, there are other types of flooding, such as deepwater and floating rice cultivation, where crops endure inundation up to several meters. Similar flooding stresses have been reported by researchers such as Bailey-Serres et al. (2010), Fukao et al. (2006), and Mackill et al. (2012).

Africa experiences similar types of flooding, consistent with global reports (Fukao et al., 2006; Bailey-Serres et al., 2010; Ismail et al., 2012; Mackill et al., 2012). Heavy rains can trigger flash floods, affecting both germination for directly seeded rice and submerging emerged seedlings for several weeks. Long-term water stagnation is another prevalent flooding type across African countries, characterized by the accumulation of water over an extended period during the rice-growing season, partially submerging crops (Agbeleye et al., 2019). Moreover, some coastal regions in Africa, such as Gambia and Guinea-Bissau, are prone to coastal floods, particularly in mangrove areas (Sakagami and Kawano, 2011). Additionally, there are regions where crops suffer from long-term complete submergence for over a month, as observed in areas cultivating deepwater and floating rice, notably in countries such as Chad, Mali, and Niger (Sakagami and Kawano, 2011).

4.3 Impact of floods on rice production and food security

Adverse impacts of floods have been observed all over Africa, posing significant losses to crop production. These impacts encompass failures in rice germination for flooded soils, crop losses resulting from flash floods, lodging of rice plants, and diminished vigor in cases of long-term stagnant flooding (Agbeleye et al., 2019). However, addressing these challenges in African rice farming is complicated by limited information and the scarcity of flood-tolerant rice varieties, leaving farmers highly vulnerable to climate extremes such as flooding (Akinyoade et al., 2014).

One region profoundly affected by flooding is Northern Ghana, where Atanga and Tankpa (2021) reported massive crop losses due to inundation, significantly affecting local food security. In Tanzania's Kilombero floodplain, rice yields have dwindled to a mere 1 tonne per hectare, with water-control challenges cited as a contributing factor for this agricultural setback (Kwesiga et al., 2020). West Africa, too, has faced the harsh consequences of long-term complete submergence, resulting in severe crop losses (Kawano et al., 2009; Sakagami et al., 2009; Sakagami and Kawano, 2011). In Uganda, over 2,000 acres of rice fields suffered significant damage due to floods, resulting in substantial yield losses (Anna et al., 2019).

Africa Rice Center (AfricaRice) (2018) noted that approximately 22% of rice production losses in Nigeria in 2012 were attributed to floods, primarily linked to the use of susceptible rice cultivars. Burkina Faso experienced a similar challenge, with an estimated 50% of the irrigated rice ecosystem suffering inundation, while Rwanda encountered 40% yield losses due to comparable circumstances [Africa Rice Center (AfricaRice), 2011]. A survey conducted by the Africa Rice Center in 2009–2010 reflected farmers' perceptions of flooding impacts, indicating an average yield loss of 27% across the rice ecosystem, with losses of 34, 27, and 25% in irrigated, rainfed lowland, and rainfed upland areas, respectively. Reed et al. (2022) reported that between 2009 and 2020, nearly 12% of people in Africa experienced food insecurity due to floods. Agbeleye et al. (2019) concurred that floods can result in losses ranging from 10 to 100%, depending on factors such as the rice cultivar., growth stage, flood duration, depth, and floodwater characteristics, as highlighted in Mackill et al. (2012). Akinyoade et al. (2014) found that only farmers using climate-resistant crop varieties and diversifying their crops were less sensitive to weather extremes.

Floods are recognized for inhibiting gaseous exchange in plants by a factor of 10,000 times and disrupting normal respiration, making them particularly lethal to crop plants (Fukao et al., 2006). This interference with the plant's ability to respire and carry out essential metabolic functions leads to severe damage and even total crop losses, consequently causing acute food shortages.

5 Overcoming flooding impacts

5.1 Research and global remarkable success on flood-tolerant rice

5.1.1 Anaerobic germination for direct-seeded rice

Significant progress has been made in the identification and development of flood-tolerant rice varieties, as evidenced by a body of research (Mackill et al., 2012; Singh et al., 2017b; Kato et al., 2019; Mondal et al., 2020). This progress encompasses the characterization of morphological, physiological, molecular, and metabolic traits associated with flooding tolerance, as reported in the studies by Panda and Barik (2021) and Singh et al. (2017b). It is worth noting that most of these achievements have been concentrated in Asia as compared to other regions. In direct-seeded rice, the establishment of crops is particularly vulnerable to oxygen limitations associated with floods. Yamauchi et al. (1993) observed limited survival and uneven crop establishment when characterizing rice germination in flooded environments, even at relatively shallow depths of 2 to 5 cm. Under more stringent screening conditions, flooding at greater depths can lead to severe crop losses, as documented by Ismail et al. (2012).

Numerous studies have examined various rice accessions for variations in tolerance under oxygen-deprived conditions, with notable contributions from researchers such as Angaji et al. (2010), Baltazar et al. (2019), and Yang et al. (2022). High expression and increased activities of a key enzyme, α-amylase, are crucial for ensuring the availability of sugars, which are essential for escaping stress (Ismail et al., 2009). It has been observed that cultivars capable of tolerating inundation during germination efficiently break down starch reserves to fuel the growing embryo and facilitate coleoptile access to air (Kretzschmar et al., 2015).

Furthermore, coleoptile elongation has been identified as a key factor determining rice survival in flooded soils and is now widely used in screening processes (Hsu and Tung, 2015; Zhang et al., 2017; Kuya et al., 2019; Pucciariello, 2020; Su et al., 2021; Thapa et al., 2022). Researchers have also identified the involvement of hormones, such as ethylene, specific enzymes such as α-amylase, ADH, and PDC, and major QTLs such as AG1 and AG2 in flood tolerance. This understanding has led to the development of flood-tolerant, high-yielding rice varieties through the introgression of these QTLs, and these varieties have been introduced to farmers (Mondal et al., 2020). The introduction of these introgressed cultivars has significantly improved germination and yield compared to previously used susceptible cultivars.

5.1.2 Flash flooding tolerance

In the event of flash floods, farmers' fields are completely submerged, which has a profound impact on crop survival and recovery (Septiningsih et al., 2009). Researchers have characterized Sub1, a quantitative trait locus (QTL) housing the Sub1A gene responsible for vegetative complete submergence tolerance (Xu and Mackill, 1996). Cultivars carrying the Sub1A1 allelic form of this gene were identified as capable of overcoming the stress and maintaining high underwater photosynthetic efficiency (Singh et al., 2020).

Studies have revealed that the primary mechanism associated with this tolerance is a quiescence strategy (Bailey-Serres et al., 2010; Pucciariello and Perata, 2013). Tolerant cultivars successfully withstand flash floods, displaying non-elongation, high survival rates, conservation of energy reserves, and improved post-submergence recovery (Fukao et al., 2006; Bailey-Serres et al., 2010; dos Santos et al., 2017). Additionally, Pedersen et al. (2009) emphasized the importance of gas films in enhancing submergence tolerance, with these micro-layers contributing to aeration even under stressful submergence conditions.

Notably, the Sub1 gene has been introgressed into popular mega varieties through marker-assisted backcrossing (Mackill et al., 2012). Consequently, farmers in Asia have been utilizing improved Sub1 varieties, including IR 64 Sub1, Swarna Sub1, Ciherang Sub1, Samba Mahsuri Sub1, and BR 11 Sub1, which have significantly enhanced yield under stress conditions.

5.1.3 Advances in stagnant flooding

Lowland areas often accumulate water for extended periods, partially submerging the crops, leading to a range of stressors affecting tillering, fertility, lodging, grain quality, and yield (Chattopadhyay et al., 2021). This challenge is particularly prevalent in low-lying fields prone to flooding. Some cultivars completely fail to survive during prolonged water stagnation.

In a study by Vergara et al. (2014), the response of 626 accessions partially submerged with 50–60 cm of water up to maturity was investigated. Stagnant flood-tolerant genotypes were characterized by moderate elongation, in contrast to semi-dwarf and fast-elongating accessions, which exhibited poor performance and low survival rates. Additionally, tolerant lines displayed minimal starch depletion compared to intolerant ones. Consequently, tolerance was attributed to factors such as moderate elongation, enhanced tillering capacity, reduced starch depletion, and increased fertility.

Singh et al. (2017a) reported the identification of 36 QTLs related to survival, growth traits, and yield under stagnant flooding conditions, primarily clustered on chromosomes 3 and 5. Chattopadhyay et al. (2021) identified 17 QTLs for partial submergence using a mapping population derived from a tolerant genotype, Rashpanjor, and Swarna, a widely grown high-yielding variety. Kato et al. (2019) highlighted IRRI119, IRRI154, and OR142-99 as released varieties with the ability to withstand stagnant flooding.

5.1.4 Deepwater-adapted cultivars

Internode elongation has been recognized as a dominant mechanism for overcoming deepwater stress (Hattori et al., 2011). Tolerant cultivars maintain increased internode elongation to stay in contact with air, in contrast to non-elongating rice types.

Since the discovery of the SNORKEL genes, SK1 and SK2, significant progress has been made in elucidating and confirming the mechanisms controlling tolerance (Hattori et al., 2009; Singh et al., 2017b). Additionally, the role of ethylene has been found to promote rapid internode elongation as a strategy for escaping water (Hattori et al., 2009). Importantly, once water recedes, deepwater-adapted cultivars keep their reproductive parts above the ground, a feature referred to as "kneeing ability" (Singh et al., 2017b; Nagai and Ashikari, 2023).

Tolerant cultivars exhibit rapid growth, with a significant increase in height, equivalent to up to 25 cm per day (Singh et al., 2017b). Some of the most frequently cited varieties with improved performance in deepwater conditions include C9285, Bhadua, and BRRI Dhan91 (Shalahuddin et al., 2020; Nagai and Ashikari, 2023). These varieties have been instrumental in enhancing the understanding of the mechanism of tolerance in deepwater and improving resilience through QTL mapping in breeding programs.

5.2 African progress on characterization and development of flood-tolerant rice

5.2.1 Anaerobic germination

Overreliance on direct seeding has exposed African farmers to the challenges of flooding caused by unpredictable rains (Kuya et al., 2019). The inundation of fields reduces oxygen availability to germinating seeds, hindering successful crop establishment and necessitating costly replanting. Despite these drawbacks, direct seeding remains a highly favored method due to its water-, labor-, and time-saving advantages (Darko Asante et al., 2021). In response to the anaerobic stress caused by flooding, various initiatives have been undertaken in Africa, including screening for stress-tolerant rice. In a study by Agbeleye et al. (2019), a screening of *Oryza glaberrima* identified five accessions with higher percent survival rates during anaerobic germination compared to the tolerant check variety, Khao Hlan On. These accessions are TOG 5980, TOG 5485, TOG 5505, TOG 16704, and TOG 8347. Currently, work is in progress to identify the QTLs associated with tolerance through bi-parental crosses, using these accessions and local sensitive cultivars.

Another screening conducted by Darko Asante et al. (2021) identified five genotypes capable of withstanding anaerobic stress. These genotypes, namely, OBOLO, ART68-12-1-1-B-B, ART64-31–1-1-B-B, CRI-1-21-5-12, and CRI-Enapa, displayed strong emergence from flooded conditions, with survival rates exceeding 75%. Presently, the Climate Smart African Rice Project, funded by DANIDA, is actively engaged in research aimed at developing flood and salinity-tolerant rice varieties. One of the project's key components is the identification of donors with tolerance to anaerobic stress during germination. The most recent achievements under this project include the identification of ten potential donors exhibiting anaerobic stress tolerance during germination (Mwakyusa et al., 2023). These donors are as follows: Afaa Mwanza 1/159, IB126-Bug 2013A, Kanamalia, Kubwa Jinga, Magongo ya Wayungu, Mpaka wa Bibi, Mwangaza, Rojomena 271/10, Wahiwahi, and Tarabinzona. They were selected based on both phenotypic tolerance and genomic values. The donors hold significant potential for future work involving QTL mapping with bi-parental or multi-parental populations.

5.2.2 Short-term vegetative submergence

In cases where rice crops are completely submerged at the early stages of establishment, even for short durations, survival is compromised, and recovery is uncertain. Many lowland rice production areas in Africa are prone to frequent floods, which can devastate crop growth (Diagne et al., 2013b). One historically significant discovery in addressing this issue is the Sub1 QTL, a major genetic locus controlling tolerance to complete submergence (Xu and Mackill, 1996). This QTL facilitates tolerance by conserving energy as a survival response (dos Santos et al., 2017). Sub1 has shown promise and has been beneficial to African farmers in flood-prone rice-growing areas.

In Africa, a significant milestone was achieved through the Stress-Tolerant Rice for Africa and South Asia (STRASA) project, a collaboration between the International Rice Research Institute (IRRI) and the Africa Rice Center. This initiative employed marker-assisted backcrossing (MABC) to develop submergence-tolerant varieties integrated with high yields and preferred recurrent parents. The project deemed varieties successful only if they exhibited at least a 1-tonne per hectare yield gain under flooding stress compared to the recurrent parent, with no yield penalties under non-stress conditions. Notable varieties resulting from this project include FARO 66 and FARO 67, which have shown the ability to overcome short-term complete submergence.[1] These varieties have become popular and are widely grown in West Africa.

In another study, Kawano et al. (2009) investigated a number of rice cultivars with African and Asian origins for their tolerance to 7 days of flash flooding. The conclusion was that African rice cultivars suffer from short-term complete submergence due to their elongation escape strategy, which leads to lodging and limited recovery post-de-submergence. Akinwale et al. (2012) evaluated 20 rice varieties completely submerged for two weeks and found that Sub1 mega varieties sourced from IRRI had higher survival rates and yields compared to non-Sub1 cultivars of African origin. Low survival and high yield reductions were observed for varieties with increased stem elongation, such as FARO 57 and FARO 52.

Anna et al. (2019) investigated cultivar responses to flash floods at the seedling stage in Uganda, revealing that none of the cultivars possessed the Sub1A-1 allele responsible for submergence tolerance. Most of the cultivars instead had Sub1A-2. Agbeleye et al. (2019) identified TOS 6454 as the best-suited accession out of 2002 *Oryza glaberrima* accessions screened for flooding tolerance. Although this accession did not surpass Swarna Sub1, a tolerant check, it significantly outperformed other accessions. This highlighted that most *Oryza glaberrima* varieties are not suited for short-term complete submergence but are more adapted to deepwater elongation. Recently, El Dessougi et al. (2022) screened 20 rice varieties from Sudan and South Sudan, including a known tolerant check, FR13A, for flash flooding tolerance. The results indicated nearly zero survival percentages for the cultivars, except for the tolerant check, which showed a 42.5% survival rate. Hence, ongoing research efforts remain essential to address the challenges faced by numerous African countries grappling with flooding stress.

5.2.3 Stagnant flooding

The prolonged accumulation of water in lowlands, resulting in the partial submergence of rice crops, is indeed a devastating issue. This condition makes the crops susceptible to lodging, which, in turn, affects growth, yield components, and overall productivity. Although this stress is prevalent in many rice-growing regions and significantly

1 Source: https://strasa.irri.org/home.

impacts yields, there is limited knowledge on how to effectively mitigate it. Agbeleye et al. (2019) conducted a screening of accessions for stagnant flooding and identified four accessions that exhibited higher grain yields (gm-2) compared to the best check, IRRI 119. These accessions were IG 48, Gervex 2,674, IG 133, and TOG 7148.

In a study by Sakagami et al. (2009), five cultivars, namely, Banjoulou, Nylon, IR71700-247-1-1-2, IR73020-19-2-B-3-2B, and Ye'le´1A, were used to investigate their response to partial submergence for a duration of 37 days at a water depth of 35 cm. Among these cultivars, only Ye'le´ represented *Oryza glaberrima*, while the rest were *Oryza sativa*. Ye'le´ is known for its strong escape response to deepwater conditions through elongation, but interestingly, it exhibited the lowest elongation in response to stagnant flooding.

Sakagami et al. (2013) reported that partially submerged rice cultivars experienced minimal growth effects compared to prolonged complete submergence. Another study by Oteyami et al. (2018) found that TOG 5810, an *Oryza glaberrima* variety, is well adapted to partial flooding. This cultivar displayed improvements in terms of a 1,000-grain weight while maintaining fewer empty grains per panicle. Currently, stagnant flooding is a significant concern addressed by the Climate Smart African Rice Project, which aims to develop rice varieties capable of withstanding water stagnation in lowland fields. This research is crucial for finding solutions to this challenging issue and improving rice production in flood-prone areas.

5.2.4 Deepwater rice

Prolonged flooding conditions, where rice crops are completely submerged, have devastating consequences for farmers. While this stress is most prevalent in some countries around the Niger Valley in Western Africa, total crop losses for less adapted rice varieties are a common occurrence. In some instances, water can accumulate to depths exceeding 1 meter for more than a month, hindering crop establishment and critical management practices. Interestingly, research and reports on this stress date back to the early 1900s, primarily focusing on countries such as Niger, Mali, Nigeria, Senegal, Gambia, Sierra Leone, Mauritania, and Benin (International Rice Research Institute, 1977). Local cultivars, mainly of the *Oryza glaberrima* species, were used by farmers but exhibited very low yields. In response to deepwater flooding, several West African countries invested in research. For example, in Mali, a number of *Oryza sativa* cultivars were introduced and tested in the 1960s, leading to the identification of varieties such as Malobadian, Indochina G, Nang Kiew, Khao Gaew, and Mali Sawn, which were best suited for deepwater conditions, with yields ranging from 3.7 to 4.5 t/ha, and were subsequently commercially released.

In Niger, a local variety called Demba Heira with an average yield of 3.6 t/ha was successfully appreciated and cultivated in deepwater. In the 1950s, Nigeria conducted evaluations of *O. glaberrima* for deepwater cultivation, identifying promising cultivars such as Badane, Tatan, Don Boto, and Farin Iri. In the 1960s, varieties such as Mali Ong, Godalaki, and Indochina Blanc were added to the list following intensive testing. The introduction and evaluations of *O. sativa* in Guinea and Sierra Leone resulted in the release of Indochina Blanc, which has been extensively cultivated in these two countries. Futakuchi et al. (2001) studied the response of African rice to submergence tolerance over a duration of three weeks. The study revealed that *O. glaberrima* exhibits greater tolerance and avoidance strategies through stem elongation compared to *O. sativa* when subjected to prolonged complete submergence. Sakagami et al. (2009) explored the physiological differences between Asian and African rice for long-term complete submergence. Seedlings were completely submerged for 31 days with a 50 cm water depth, including IRRI Sub1 checks. All *O. glaberrima* cultivars survived the stress with increased shoot elongation compared to Asian rice, while all Sub1 cultivars such as FR13A failed to survive. Cultivars such as Nylon and Ye'le´1A were confirmed to be adapted to deepwater following a similar trial involving submergence for 37 days with an 80 cm water level.

Furthermore, Sakagami et al. (2013) conducted another screening for complete submergence over a duration of 32 days. The findings showed an average survival rate of around 90% for African rice, while Asian rice cultivars exhibited survival rates of 40–50%. The Sub1 checks failed to survive the stress, displaying less than 5% survival. One outstanding survival case was displayed by CG14, an *Oryza glaberrima* cultivar., which showed 100% survival after 32 days of complete submergence and significant recovery. Strategies such as faster shoot elongation, anaerobic tillering, larger leaf area extension, higher photosynthetic rate, and the maintenance of PSII maximum efficiency are potentially used by *O. glaberrima* to survive prolonged deepwater conditions. Through the STASSA project, two cultivars, Kolondieba 2 and Kadia 24, were developed for lowland deepwater ecosystems. These cultivars were well distributed in Mali, covering farmers' fields prone to long-term deep flooding, and have shown the ability to survive stress with improved yields (see footnote 2).

In a recent study, Luo et al. (2023) used African cultivated rice to study the mechanisms employed for survival in deepwater conditions. The findings indicated that internode elongation is highly expressed in deepwater-adapted cultivars. Additionally, genes promoting internode elongation, such as SNORKEL (SK1/SK2), SEMIDWARF1 (SD1), and ACCELERATOR OF INTERNODE ELONGATION 1 (ACE1), were characterized by increased internode elongation in the presence of SK genes. Among the allelic forms of the SK2 gene, SK2-B was found to be highly significant in strongly accelerating internode elongation during flooding. Cultivars such as CG14, C8992, RAM3, C8872, C8991, C8892, and W0844 displayed the highest internode elongation and can hence be considered useful resources for variety development.

5.3 Potential advantages of flood-tolerant rice in Africa

Agbeleye et al. (2019) highlighted WITA 4 as an outstanding variety, surpassing the known checks IRRI 119 and IRRI 154 in both survival and yields. In stagnant flooding conditions at a 50 cm water depth for three months, WITA 4 exhibited an impressive survival rate of 78%. Most notably, the variety experienced only a 4% reduction in yield compared to the control conditions. Under stress conditions, it yielded 385 g/m^2, equivalent to 3.85 t/ha, while IRRI 119 and IRRI 154 yielded only 220 and 144 g/m^2, respectively. Therefore, the adoption of this variety for cultivation and as a donor is of significant importance and has the potential to bring about a revolution in fields prone to stagnant flooding.

Africa Rice Center (AfricaRice) (2020) reported its results of the evaluation of FARO 66 and 67, which were released in Nigeria in 2017. These flood-tolerant varieties were derived from the Sub1-introgressed mega varieties WITA 4 and NERICA-L 19 through marker-assisted breeding. The average yield advantages ranged from 10 to 80 times during submergence and a 6–29% higher yield when there was no stress compared to their recurrent parents. The UNDRR (2017) highlighted that FARO 66 was superior to its recurrent parent WITA 4 (FARO 52); hence, under submergence, it yielded 80 times, and under non-submergence, it had a yield gain of 6–11%. FARO 67 yielded 10 times under submergence, while under non-submergence, it had a 10–29% yield advantage compared to its recurrent parent NERICA- L19 (FARO 60).

Another study by Ulzen et al. (2022) compared the performance of improved varieties to lowland ecology, among which FARO 66 and 67 were included. The farmers selected FARO 66 as their preferred variety over the others due to its high yield and large panicles. The comparison of varietal resilience to submergence when wet seeded or transplanted using FARO 66, FARO 67, and a local check WITA 9 in Cote d'Ivoire indicated that the yields of two submergence varieties (FARO 66 and FARO 67) are not affected by either the growing season or crop establishment method unlike the local check (Devkota et al., 2022). The yields of the submergence tolerant varieties, regardless of the growing season and establishment method, were 1.1–4.5 t/ha higher than those of WITA 9. FARO 66 and FARO 67 were declared among the Sub1 climate-resilient variety with a yield advantage of 1–3 t/ha over the original varieties (CGIAR, 2021). Therefore, with such yield advantages, farmers adopting these varieties are more likely to be successful and overcome food scarcity during harsh weather.

5.4 Learning from the experiences in Asia

Numerous studies conducted in Asia have provided valuable insights into the mechanisms of stress tolerance in rice and the subsequent development of tolerant rice varieties. This wealth of research has made Asia a prime example from which valuable lessons can be drawn regarding how farmers have benefited from the adoption of stress-tolerant rice varieties. These studies have demonstrated the positive impact of utilizing such varieties. Mondal et al. (2020) conducted an evaluation of 10 cultivars for anaerobic germination. These cultivars were subjected to dry direct seeding, and seeds were submerged with a water depth of 3–5 cm for 21 days. Their findings revealed that the popular varieties with anaerobic germination QTLs AG1 and AG2 demonstrated a significantly higher yield of 2.8 t/ha compared to their counterparts lacking these QTLs. Furthermore, the varieties introgressed with AG QTLs exhibited a greater number of tillers, indicating their potential for improved rice production.

Similarly, Mackill et al. (2012) reported the results of multisite evaluations of Sub1 varieties paired with their non-Sub1 counterparts. These evaluations involved subjecting the rice to complete submergence for more than 5 days. Notably, Swarna Sub1 and Samba Mahsuri Sub1 yielded 3.67 and 3.8 t/ha, respectively, in contrast to their non-Sub1 counterparts, which yielded 2.34 and 2.1 t/ha. The Sub1 varieties exhibited yields that were twice as high during extended periods of submergence compared to the non-Sub1 varieties. Furthermore, submergence-tolerant cultivars exhibited characteristics such as greater chlorophyll retention and improved seedling recovery.

Moreover, farmers in countries such as India, Bangladesh, Nepal, the Philippines, and Myanmar have adopted Sub1 rice varieties. These include popular varieties such as Swarna Sub1, IR64 Sub1, BR11 Sub1, and Samba Mahsuri Sub1. The farmers assessed various traits, including survival, recovery, tillering, plant height, panicle length, grain color, length, and quality, post-harvest qualities, and overall yields. The Sub1 varieties consistently outperformed locally used cultivars in the criteria assessed by the farmers. This not only contributed to improved overall productivity but also had a positive impact on food availability and living standards.

6 Conclusion

This review has examined the progress in Africa's development of flood-tolerant rice varieties. While some strides have been made, the region's achievements remain limited, underscoring the critical importance of flood-tolerant rice varieties for improving productivity and ensuring food security. The scattered nature of information on developing flood-tolerant rice varieties highlights the need for effective coordination and thorough documentation. Despite the limited number of flood stress-tolerant varieties currently available in the region, it is imperative to ensure their widespread dissemination in flood-prone rice cultivation areas. This requires studying farmers' perceptions, adoption rates, and the performance of these varieties as data on these aspects are scarce. Such studies can provide valuable insights into crop survival, quality, and overall performance, potentially leading to significant improvements in farmers' harvests and food availability. Nonetheless, it is essential to recognize that further efforts are still needed in the identification and development of flood stress-tolerant varieties, given the alarming intensity and frequency of floods in Africa. Furthermore, there is also a crucial need for the development of rice varieties that can withstand multiple types of flooding. Currently, no such varieties are available, even though the same ecological regions can experience diverse types of flooding. Therefore, the future success of Africa's rice sector hinges on dedicated and productive research efforts, coupled with effective dissemination and adoption strategies.

Author contributions

LM designed the study concept, conducted the literature review, and drafted the manuscript. SD, MH, MCH, RM, and NK edited the study concept and reviewed the manuscript. 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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Bundled climate-smart agricultural solutions for smallholder farmers in Sri Lanka

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Smallholder farmers are among the most vulnerable to climate shocks in Sri Lanka. Lack of education and technical skills, poverty, risks inherent to agricultural investments, limited assets, and financial capital are major reasons for low investments in enhancing adaptive capacity. The study explores the use of agricultural technologies in improving smallholder resilience to water-related disasters and their opportunities for recovery. We tested four bundled services to promote climate-smart agriculture practices namely weather index insurance (WII), agronomic advisories dissemination via SMS, weather services, and climate-resilient seeds of maize and rice. The integrated solutions are referred to as Bundled Solutions of Index Insurance with Climate Information and Seed Systems (BICSA) to manage agricultural risks in Sri Lanka. The study conducted the bundled solutions in three agroecological regions spread over five districts and covering more than 2,500 farmers in three cropping periods of *Maha* and *Yala* seasons. The results demonstrate that providing bundled solutions significantly protects smallholders against moderate drought events. The satellite-based weather index insurance can offset the long-term consequences of severe yield losses and mitigate the long-term drop in farm productivity. Our findings demonstrate the importance of bundled insurance to mitigate financial risks associated with extreme weather events and enhance resilience to climate change among vulnerable smallholders. It is evident from the study promoting a viable business model among seed companies, insurance companies, and technological partners, along with public institutions such as agricultural extension services can help production-level improvements and develop strategies at both the farm and policy levels that will support a transition to a more resilient farming system.

KEYWORDS

climate-smart agriculture, drought-prone farmers, extension services, weather index insurance, public-private partnership, Sri Lanka

1 Introduction

Over the last two decades, floods and droughts have been identified as two of the most devastating consequences of the climate crisis (Browder et al., 2021). The extreme weather events had serious implications for agriculture and food production, along with a wide range of broader impacts on the livelihood and wellbeing of the affected communities. In the last two decades, floods and drought accounted for 53% of all documented natural disasters, affecting 2.4 billion people and killing 168,000 (CRED, 2020). Droughts and floods have cost US$764 billion in damages in the period 2000–2019, with floods being the most recurrent disaster. Storms have resulted in an additional US$1,390 billion in damages, much of it from storm-related flooding (Browder et al., 2021). Climate change has made extreme weather events more severe by altering the frequency, timing, intensity, and duration, resulting in unprecedented extremes (Amarnath, 2020; Browder et al., 2021). The IPCC (2018) projected increasing global temperatures with higher and longer daily temperature extremes at a global scale. Increasing temperature generally results in an increase in potential evapotranspiration, largely because the water-holding capacity of air is increased (IPCC, 2021). It is highly likely that this development would lead to a change in the hydrologic cycle, including increased atmospheric water vapor and changes in precipitation patterns as well as changes in groundwater and soil moisture.

It has been estimated that by 2050, rising populations in flood-prone lands, climate change, deforestation, loss of wetlands, and rising sea levels are expected to increase the number of people vulnerable to flood disasters to 2 billion (UNU, 2004). At the same time, with changes in the hydrologic cycle, several water-scarce regions are experiencing severe water scarcity. High temperatures will further lead to an increase in land evapotranspiration, creating more conditions of water stress. In contrast to water stress, floods are projected to increase across more than half of the world's region, varying in magnitude across river basins (World Bank, 2016). In addition to these climate change impacts, human-induced factors affect the hydrological systems, and water resources. Most prominent are the land management practices that alter the availability of water resources and increase the risks of floods. Human-induced climate change has contributed to increased agricultural and ecological droughts in some regions due to increased evapotranspiration (IPCC, 2021).

These events and anthropogenic interferences will increase the frequency and intensity of floods and droughts at the regional scale as indicated by the climate model projections (He et al., 2020). This leads to the consideration of developing instruments at the regional scale and local scale to mitigate challenges from extreme weather events. To increase risk resilience at the regional and local level, it is imperative to invest in the exchange of tools, knowledge, and resources to systematically prepare for and respond to floods and droughts (Browder et al., 2021). Integrating different information drawn from existing climate, agriculture, risk, and socioeconomic datasets can increase preparedness for floods and droughts. The various datasets integrated together provide an opportunity for studying climate variabilities and their implications on agriculture and food production. The integration of such heterogeneous datasets can be used to increase risk resilience at the community level.

The development of index-based weather insurance products to compensate agricultural households because of extreme weather events is one such mechanism (Aheeyar et al., 2021; Amarnath et al., 2021). It is a cost-effective way of safeguarding against climate uncertainty, thereby protecting smallholder families from food insecurity and hunger and giving them the confidence to invest in and improve their farming enterprises (Manojkumar et al., 2003; Bryla and Syroka, 2007; Delavallade et al., 2015).

Index-based flood insurance is an innovative approach that integrates different information for designing the insurance product. Remote sensing-based datasets are used for mapping historical and current flood events to determine the spatial extent of the floods. Hydrodynamic models can then be developed to help determine the spatiotemporal variability of flood parameters (Malik and Amarnath, 2021). These models incorporate different time series datasets such as monthly rainfall and frequency, population involved in agriculture, number of people affected historically, flood-affected area, estimated economic loss, and yield loss of the primary crop (Matheswaran et al., 2019). The flood parameters (flood depth and duration) at daily time intervals for a specific period of time can be used to create triggers (Amarnath et al., 2017; Amarnath and Sikka, 2018) that define the insurance scheme. During extreme rainfall events, data provided by local weather stations are matched with the triggers. If the rainfall exceeds the threshold triggers, the farmers enrolled in the program are entitled to a payout. Similar exercises with different datasets, such as evapotranspiration, water deficiency, and water satisfaction index for estimating crop yield, along with the Normalized Difference Vegetation Index (NDVI), can be used for developing an index-based drought insurance scheme (Bucheli et al., 2021). The index-based insurance products can be bundled with local information and advisories such as weather information, loans, crop and water management methods, and fertilizer usage (Mukherjee et al., 2017) for climate-smart transformation to avoid climate disasters.

Countries in Asia and the Pacific are most vulnerable to water-related disasters, accounting for more than 45% of fatalities and more than 90% of the people affected by disasters (ADB, 2021). In the Asian region, eight countries, the People's Republic of China, India, Indonesia, the Maldives, Myanmar, Pakistan, Sri Lanka, and Thailand, are most affected by floods (ADB, 2013). Therefore, adaptation measures are required to sustain agricultural productivity and enhance the resilience of the agricultural system to climate change. In Sri Lanka, for example, smallholder farmers are among the most vulnerable to natural disasters. Over 27 million people have been affected by floods and droughts, with economic losses estimated at over US$2.62 billion since 1966. Considering weather insurance as a social protection tool along with other advisories, the present study focuses on the application of bundling climate-smart agriculture and risk transfer for agricultural resilience in Sri Lanka. The application of the tool earmarks the integration of global, national, and local datasets for reducing agricultural risk and vulnerability. The study explains the agglomeration of different datasets and digitization in the pathway for developing instruments for increasing agricultural resilience with the help of a case study. The main objective of the study was to provide evidence about the construction and implementation of bundled climate-smart solutions in Sri Lanka. The bundled insurance was tested in five districts—Ampara, Anuradhapura, Kurunegala, Monaragala, and Vavuniya. The distribution of bundled insurance across the farmers provides learnings that lead to key recommendations for scaling up insurance through the utilization of a sustainable business model.

2 Concept and implementation of bundling climate-smart solutions

Index-based weather insurance is an alternative adaptation measure with a financial remedy designed based on predetermined weather variables such as rainfall level, temperature, floods, and droughts (Ahmed, 2013; Afriyie-Kraft et al., 2020). The mechanism of index insurance works through triggers derived from weather indices, instead of the direct loss assessments made at the farm level (Ellis, 2017). The triggers of the weather events are set to a defined local or regional weather station (IFAD, 2017a). The premiums for the insurance are usually related to the expected income of the cost of production (Ellis, 2017). All policyholders within a region defined by the weather station receive payouts based on the same contract and measurement according to the set weather station (IFAD, 2017a). Index insurance has a uniform structure, does not require trained experts to check or confirm losses, and thus has comparatively low administrative costs. This helps to avoid loss adjustment by both the insurer and the insured, which lessens risks, enhances trust, and avoids alterations (Shahadat, 2013; Carter et al., 2014; Greatrex et al., 2015). Index insurance can operate as a stand-alone contract or be linked to credit for buying farm inputs, rendering insured farmers more credit-worthy than uninsured ones (Meze-Hausken et al., 2009).

Climate-smart technologies are critical for addressing climate change and variability that help increase agricultural productivity, enhance resilience, and lower emissions. The main constraints in adopting bundled climate-smart solutions are linked to several factors, including the high cost of inputs, lack of credit, limited access to agricultural and climate information services, institutional support, socioeconomic status, and risk-taking behavior (Figure 1). According to Mukherjee et al. (2017) and Chibowa et al. (2020), index insurance can be bundled differently. The study identifies three different ways—(i) credit bundling, (ii) input bundling, and (iii) contract farming and insurance bundling. In credit bundling, loans/credit to farmers are bundled with agricultural insurance. Bundling index-based insurance with credit may help to address these challenges by providing a means to pre-finance or defer premium payments, thus facilitating access to credit (Giné and Yang, 2009; Liu and Myers, 2012). At the same time, insurance can reduce the lending risk of farmers and the credit facility, which, in turn, is expected to increase loan amounts and potentially expand credit to currently underserved farmers (Meyer et al., 2017). Microfinance institutions (MFI) or cooperatives through which farmers access credit and other agricultural services or inputs may also strengthen the take-up of weather index insurance (WII)—which has remained below expectations in many cases—because they can increase access to insurance in rural areas and build on preexisting relationships with farmers. In addition, MFIs and cooperatives can help to reduce administrative costs and thus support the scaling up of WII (Meyer et al., 2017).

There are several examples of bundling of index insurances with inputs—(i) subsidized weather index insurance with input loans for fertilizers and modern seed for smallholder farmers in rural Ethiopia (McIntosh et al., 2013; Ahmed et al., 2020); (ii) multi-peril insurance at zero cost if farmers purchase improved seeds (any one of maize, sorghum, soya, and sunflower) (Bulte et al., 2020); and (iii) bundled insurance with seeds (Kilimi Salama in Kenya) and fertilizers (IFFCO Tokio in India). In both the credit- and input-linked insurance bundles, the bundling can take two different forms. In the first scenario, the insurance product is compulsory for the smallholders when using a complementary product or service, such as inputs or credit, and the insurance component may be invisible to the farmer. The second scenario is where the insurance product is voluntary and presented as part of a menu or solution options (Agbon, 2020).

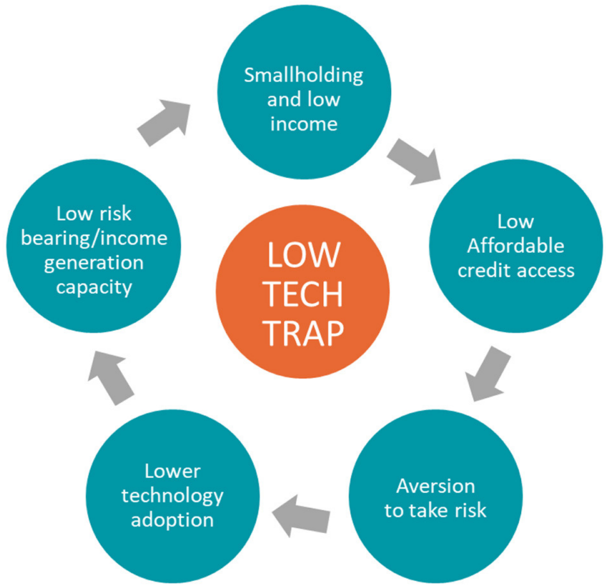

FIGURE 1
Challenges of bundled climate-smart practices among smallholder farmers in enhancing adaptive capacity. Source: Authors.

The contract farming and insurance bundling include two sub-forms—buyer collaboration and information and support services. In the buyer collaboration model, the end buyer of the contract (i.e., the company buying the farm output) offers bundled insurance along with loans to the farmers. The insurance in such cases is mandatory along with the credit or inputs (e.g., NWK Agri Services in Zambia). In the second model, the contract buyer offers insurance voluntarily. The insurance provides a set of services that include support services (like weather advisory) to maximize the value proposition to the farmer (example of PepsiCo in India procuring potato from contract farmers). There are other innovations linked to index insurance, for example, linkage with safety nets, where employment opportunities are created for resource-poor farmers to pay for insurance premiums. Farmers are engaged in resource management such as tree plantation, and through their investment in labor, they obtain insurance certificates to guarantee payouts in the event of drought affecting crop production (Brans et al., 2010; OA, 2010). This approach has been tested in northern Ethiopia by Oxfam America, private insurers, cooperative unions/micro-financial institutions, farmers, and government agencies that run the current Productive Safety Net Programs (PSNP) in the country (Tadesse et al., 2015). Besides being bundled with related value-added services, such as agronomic advisory and input loans, many index insurance services have been cross-sold with other types of insurance, such as health or life insurance. This approach provides farmers with comprehensive coverage against a range of shocks and allows providers to cross-subsidize their index insurance services and even educate farmers through trusted partners (Raithatha and Priebe,

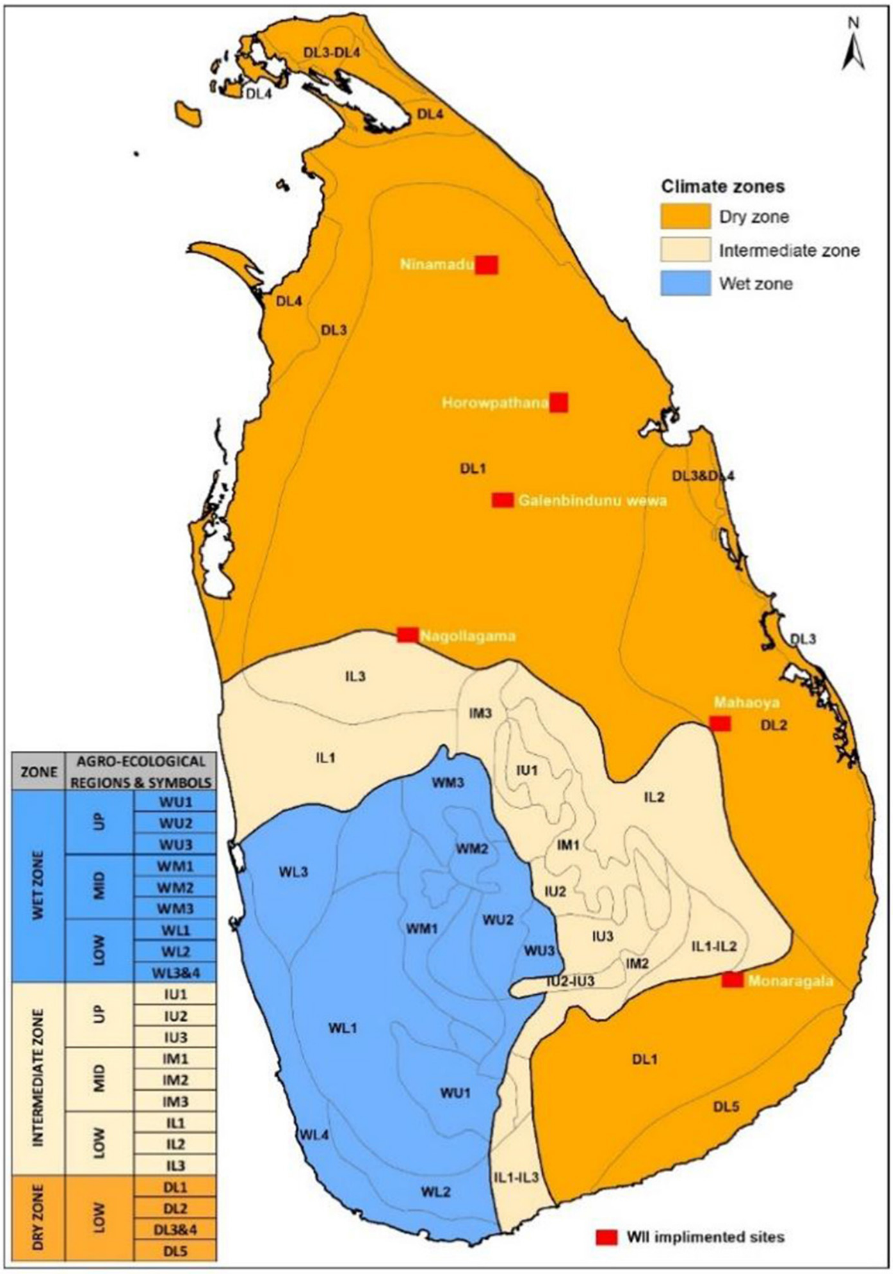

FIGURE 2
Map shows study sites piloted during three (2020–2021, 2021–2022 *Maha,* and 2021 *Yala*) cropping seasons. Source: Authors.

2020). For example, Econet's ZFU EcoFarmer Combo provides services to farmers of the Zimbabwe Farmers' Union.

2.1 Application of earth observation for crop insurance

Earth observation plays a crucial role in the application of crop insurance by providing accurate and timely data to assess crop health, monitor agricultural conditions, and facilitate insurance claims processing. Earth observation satellites, equipped with remote sensing instruments, can capture high-resolution imagery of agricultural fields at various intervals throughout the growing season. These data help insurance companies and agricultural experts monitor crop health, detect anomalies, and estimate potential yields (IFAD, 2017b; Omia et al., 2023). By comparing current conditions to historical data, they can assess the impact of weather events and other factors on crop performance (Schauberger et al., 2020).

Earth observation satellites equipped with remote sensing sensors, such as optical and radar instruments, can monitor crops from space (Omia et al., 2023). The increased availability of open-source data to seamlessly access historical to current satellite images can help insurers to track vegetation health and growth patterns and identify potential risks such as pest infestations, diseases, or drought stress. Such regular monitoring of the insured areas can help insurers make informed decisions about insurance coverage and identify areas requiring additional support. In recent years, the advanced capabilities of earth observation data, combined with advanced data analytics and machine learning algorithms, can be used to estimate crop yields accurately (Elavarasan et al., 2018; Virnodkar et al., 2020). This information is essential for setting appropriate insurance premium rates and determining insurance payouts in the event of crop losses. Accurate yield estimation reduces the risk of overpaying or underpaying claims.

Furthermore, earth observation data are regularly used to study the historical to current weather patterns and identify climate hotspots for insurers to develop tailored parametric index insurance products to ensure wider adoption of risk transfer mechanisms to changing climate conditions. The study highlights key satellite data products, for example, satellite-derived products such as Climate Hazards Group Infrared Precipitation with Stations (CHIRPS), Global Precipitation Measurement (GPM), Soil Moisture and Ocean Salinity (SMOS), Soil Moisture Active Passive (SMAP), and Normalized Difference Vegetation Index (NDVI)/Enhanced Vegetation Index (EVI), and high-resolution data from the European Space Agency (ESA) Sentinel-1 and Sentinel-2 and the United States Geological Survey (USGS) Landsat will be used for the monitoring and claim assessment. Index insurance is increasingly being recognized as an innovative approach to eliminating issues in the existing indemnity-based approach. By harnessing the power of earth observation and combining it with advanced analytics and data-driven methodologies, crop insurance companies can enhance their risk management capabilities, provide timely and accurate insurance services to farmers, and contribute to the resilience of agriculture in the face of climate change and other environmental challenges.

3 Implementation of bundled insurance in Sri Lanka

3.1 Study area

Sri Lanka is a tropical island nation and is becoming increasingly vulnerable to climate change, which significantly impacts the country's food production, people's livelihood, and natural ecosystem. As Sri Lanka is located in the Indian Ocean south of India, it receives rainfall through four monsoon seasons, such as First Inter Monsoon (FIM—March to April), Southwestern Monsoon (SWM—May to September), Second Inter Monsoon (SIM—October to November), and Northeastern Monsoon (NEM—December to February). There are two major cropping seasons, *Yala* (May to August) and *Maha* (September to March), which coincide with the four rainy seasons, and crop damage is regularly reported due to frequent droughts and floods during the south-west and north-east monsoon. Rainfall distribution of the country is the central pillar of agroecological classification, and there are three climatic zones—wet, dry, and intermediate zones (Figure 2). These zones are further classified based on the elevation of land, soil type, and agricultural conditions, resulting in 24 agroecological regions (Panabokke, 1996).

The evaluation of BISCA was first tested through a pilot study conducted in the north-central province during the *Maha* season. The pilot study included maize-growing farmers selected through purposive sampling from the *Dunumadalawa Gramaniladari Division* (GND) and *Galenbindunuwewa* Divisional Secretariat Division (DSD) in the Anuradhapura District. As the sampling was non-probabilistic, care was taken to reduce bias through stratification, proper consultation, and benchmarking. Sri Lanka is administratively divided into provinces, districts, divisional districts, and GNDs at the lowest level. The decision of the sample size was mainly governed by the presence of marginal farmers (cultivating <0.25 acres) estimated through a stratification approach. The other benchmark apart from being a marginal farmer that was used for selection was agricultural income.

In Anuradhapura district, *Galenbindunuwewa* Divisional District was selected as maize cultivation is the main livelihood in this division, where more than 55,000 farmers cultivate an area of over 10,000 acres (Hiru News, 2021). Smallholder farmers (farmers cultivating 0.25 acre to 20 acres) are approximately 11,809 (Economic Census, 2013-14). According to the Economic Census (2013-14), 46.1% (5,432) are small farmers operating on land <0.25 acres. The distribution of these marginal farmers across the Divisional District was unavailable from secondary data sources; hence, crop production data at different GNDs were used. Grama Niladhari Divisions Statistics (2020) for Anuradhapura district indicates that out of the 41 GN divisions, 38 GN divisions have crop cultivation as an economic activity. This implies that, on average, there are 143 farmers engaged in crop cultivation. Therefore, given this background, 100 farmers for controlled evaluation were considered an appropriate sample size from *the Dunumadalawa Gramaniladari Division,* where most farmers primarily relied on rain for maize cultivation.

The 100 marginal farmers were selected based on the information provided by District Agricultural Officers (DAOs) and consultation with farmers' organizations at the local level identified by the DAOs. The main criterion for selecting these 100 small farmers was their agricultural income. The Household Income and Expenditure survey (2012-13) shows that the mean household income from agriculture was LKR 5,856. As this income is not representative of the present situation, this household income was inflated with an appropriate deflator to reach a representative income. The Economic Statistics of Sri Lanka (2022) shows that between 2016 and 2022, the price deflator had doubled. The benchmark was, therefore, set to LKR 12,000 as monthly agricultural income to select the farmers in the pilot study and accommodate the inflation between the periods.

Following the successful implementation of the pilot study, the BICSA program was scaled to dry zones in the five districts of the north and eastern parts of the country—Ampara, Anuradhapura, Monaragala, Kurunegala, and Vavuniya (Figure 2). These districts have similar climatic variabilities, and smallholder farmers face severe challenges in sustaining a stable agricultural income. The particular sites within the districts were selected using the stratification process through consultation with the DAOs, and farmers were identified by the farmers' organization through

TABLE 1 List of data used for implementation of bundled climate-smart solutions.

Data	Source	Duration
Satellite-based rainfall data	CHIRPS	1981–2020
Observed rainfall data	Meteorological Department, Sri Lanka	1980–2020
Field data (farmers and farm level) for BICSA enrollment	Collected through ODK	2020–2021
Administrative boundary (district, DSD, and GND)	Survey Department of Sri Lanka	2018

benchmarking (with agricultural income) during the pilot study. The second (1,321 farmers for the *Yala* season 2021) and third phase (1,000 farmers for the *Maha* season 2021–2022) of implementation covered farmers engaged in maize and rice cultivation. The distribution of the farmers across the districts is shown in Tables 6, 7.

3.2 Data

The data section on developing weather index insurance using precipitation data from CHIRPS provides rainfall amounts and distribution since 1981. The study gathers ground-based weather data from meteorological stations in the insured areas. These data serve as ground truth for calibrating and validating satellite-based observations (Table 1). Insurers use these data to set rainfall thresholds that trigger insurance payouts for drought or excess rainfall events. The study uses earth observation data from USGS Landsat and ESA Sentinel-2 images to provide insights into crop health and growth based on the Normalized Difference Vegetation Index (NDVI) to evaluate the historical insurance claim. NDVI values are often used as one of the indices triggering insurance payouts in agriculture-related index insurance products. The study developed a survey form using the Open Data Kit (ODK) for efficient enrollment of weather index insurance products among farmers.

3.3 BICSA components

The bundle intends to address both the challenges of farmers' adoption of climate-smart agriculture and strengthening partnerships among public–private actors, namely, seed companies, climate information services, and insurance companies. BICSA supports (1) improving access to climate-resilient seeds of maize and rice varieties; (2) improving farmers' access to climate-smart information services; (3) promoting the use of agronomic practices (e.g., tillage, water management advisories, and pest and weed management); and (4) access to weather index insurance to mitigate financial losses from floods and drought (Figure 3).

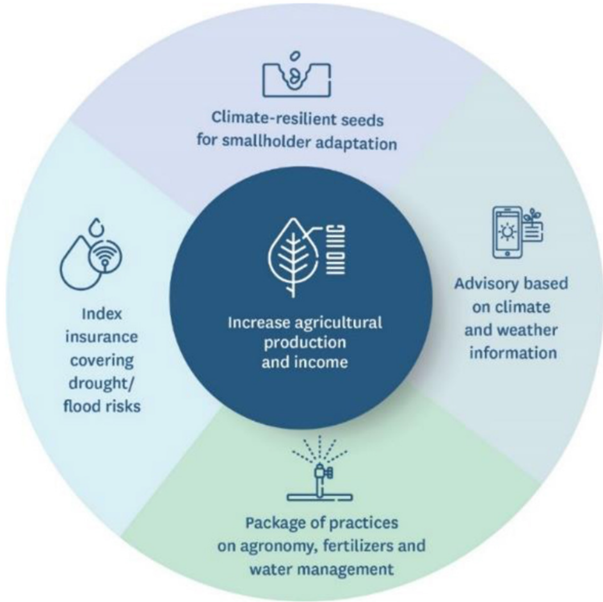

FIGURE 3
Components of climate-smart bundled solutions. Source: https://ccafs.cgiar.org/news/bundled-agricultural-insurance-solutions-climatarians-gambit.

3.3.1 Climate-resilient seeds

The most important thing for cultivation is to purchase seeds that give a good yield in any climatic condition, and because of adverse acclimate variability experienced in recent times, it is more important for the farmers to use seeds that are resistant to climate. As part of BICSA, we provide climate-resilient seeds (paddy and maize) to farmers for better yields even during floods and droughts. As the BICSA pilot project was conducted to cover different climatic zones, the seed varieties of rice crops, namely, BG 352, BG 300, BG 358, and AT 362, were distributed to the farmers. Hybrid Maize—JET 999 was provided to the farmers as climate-resilient seeds for maize farmers.

3.3.2 Climate services and agronomic advisories

Climate and agronomical advisories are more important for farmers to manage their crops safely through the efficient use of water and fertilizers. To provide the climate advisories, freely available climate forecasts were used 5 days in advance. Climate forecast information on rainfall, temperature, and wind speed is provided to farmers twice a week through SMS. Table 2 shows how the forecasted rainfall data are converted into information. For agronomical advisory services, from the beginning of cultivation to the time of harvest, the agricultural specialist works closely with the farmers. The information required for their agricultural problems, such as fertilizer use, herbicide, and pesticide application time, is provided to the farmers each week.

3.3.3 Weather index insurance design

The precipitation data required for the development of the WII product were obtained by CHIRPS rainfall products and extracted from 30 years of daily precipitation data pertaining to the study area covered by the CHIRPS pixels. WII product was designed by insurance companies using the daily rainfall data given below.

Rainfall was used to design our Meteorological Insurance (WII) products, and a single WII was designed to cover both droughts and floods, which were caused by extreme wet and dry conditions. The area considered for WII product implementation uses monthly rainfall data for approximately 30 years of historical rainfall data, which is used to determine the trigger values for drought and flood for each month of the particular season (*Yala* and *Maha*). Thus, the claim is determined for each millimeter of precipitation that increases or decreases from the trigger value determined for drought and flood. For example, as shown in Table 3, the WII trigger values for drought and flood in Nainamadu village in Vavuniya district in May, June, and July are 300 mm, 200 mm, and 200 mm (flood) and 20 mm, 2 mm, and 15 mm (drought), respectively. The increase and decrease of each millimeter of rainfall relative to the trigger values is calculated relative to the maximum payout of the maximum insurance coverage. The example shown in Table 3 pays 382.50 rupees per millimeter reduction of rainfall in May during the drought in Nainamadu, which is as high as 1,377 rupees per millimeter in June because the gap between the trigger and stop-loss is approximately only 2 mm.

3.4 Climate advisory service

Climate and agronomy advisories were provided to the enrolled farmers via SMS throughout two consecutive seasons (*Yala* 2021 and *Maha* 2021–2022) (Table 4). The climate advisories on short-term weather forecast information (rainfall, temperature, and wind speed) were provided 5 days in advance to the farmers weekly (Monday and Thursday) in Sinhala and Tamil. On the other hand, agronomy advisories were issued biweekly (on Thursdays). A focus group discussion was carried out to understand the need for specific information that was to be incorporated into the advisory. A total of 17,161 for the *Yala* 2021 pilot and 23,100 advisories for the *Maha* season 2021/2022 were issued in the two consecutive seasons, respectively.

TABLE 2 Sample advisory on rainfall classification.

Classification	Rainfall (mm) and spatial occurrence
Dry or no rain	0–2
Isolated	2–5 and rain in isolated pockets
Scattered	5–20 and rain in scattered
Fairly widespread/many places	20–50 and rain in many places
Widespread/most places	>50 and rain in everywhere

Source: Authors.

3.5 Business model implementation

The bundled insurance was implemented as a micro-model (Figure 4) where the implementing partners, namely, (i) International Water Management Institute (IWMI); (ii) Sanasa General Insurance Company Limited, Sri Lanka; (iii) Department of Agrarian Development, Sri Lanka; and (iv) CIC Agri Businesses (Pvt) Ltd., Sri Lanka, co-designed and co-implemented across pilot districts in Sri Lanka. The program was an insurer-led model with the insurance company designing the insurance product, underwriting, and taking care of regulatory compliance. IWMI

TABLE 3 Weather index insurance design for excess and deficit rainfall among pilot districts in Sri Lanka.

Deficit rainfall	Vavuniya–nainamadu			Deficit rainfall	Monragala–morawa			Deficit rainfall	Kurunegala–gajameegam		
	May	June	July		May	June	July		May	June	July
Payout 1											
Stop loss	0	0	0	Stop loss	0	0	0	Stop loss	0	0	0
Trigger	20	2	15	Trigger	15	10	25	Trigger	15	30	20
Max	8,500	3,060	8,500	Max	8,500	8,500	8,500	Max	8,500	8,500	8,500
Min	850	306	850	Min	850	850	850	Min	850	850	850
Slope	382.5	1,377	510	Slope	510	765	306	Slope	510	255	382.5
Payout 2											
Stop loss	450	350	300	Stop loss	450	450	350	Stop loss	450	450	350
Trigger	300	200	200	Trigger	300	250	250	Trigger	300	250	250
Max	8,500	8,500	8,500	Max	8,500	8,500	8,500	Max	8,500	8,500	8,500
Min	850	850	850	Min	850	850	850	Min	850	850	850
Slope	5	51	76.5	Slope	5	38.25	76.5	Slope	5	38.25	76.5
Claim	54%	77%	20%	Claim	72%	59%	29%	Claim	63%	19%	27%

Source: Authors.

TABLE 4 An example of climate and agro-advisory in different crop stages.

Crop stage	Agronomical advisory	Climate advisory
Sowing	Always be vigilant as rice bug damage can occur at the early stage of the cultivation. If eggs are observed on the leaves, collect and destroy them immediately.	Scattered showers are forecast for your area over the next 5 days (10–15 January 2021)
Growing	For efficient water management, supply water to the paddy field to a height of 5 cm during the growth stage of the plant and re-water the field after it has drained to a depth of 15 cm from the soil surface.	Dry weather with no rain is forecast for your area for the next 5 days.
Harvesting	After paddy harvesting, place the seeds on a well-cleaned cement threshing floor or tarpaulin cloth to gradually reduce the moisture content. Paddy should be spread in a layer <2 cm thick to dry.	Dry weather is forecast for your area for the next 2 days and isolated showers are likely in the next 3 days.

Source: Authors.

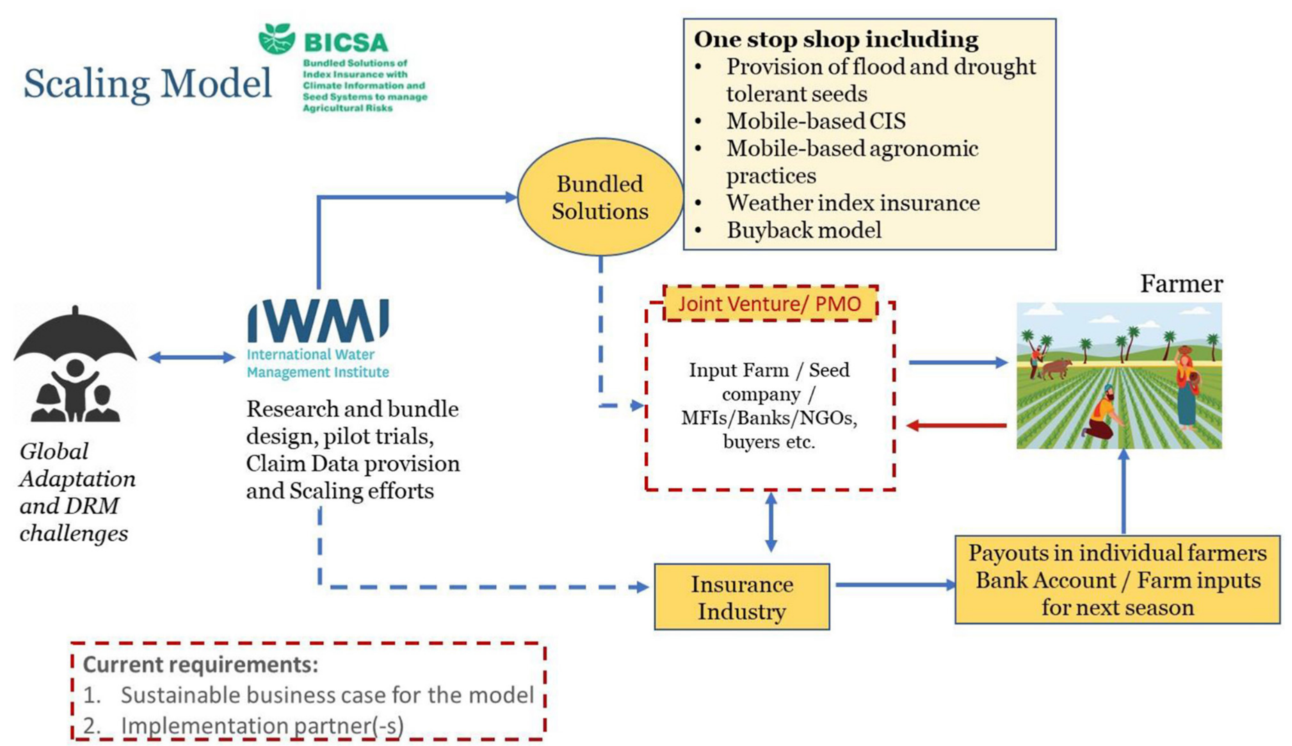

FIGURE 4
BICSA business model implementation in Sri Lanka. Source: Authors.

provided analysis of remote sensing and weather data (historical rainfall and forecasts), which formed inputs for the weather index. The insurance contract design was further tested and adjusted before the insurance staff, agents, and other delivery channels were trained. Table 5 provides a summary of the roles and responsibilities of partners for scaling BICSA solutions.

The primary focus of the business model was to provide an integrated one-stop-shop service delivery model for smallholder farmers to promote climate-smart bundled solutions that accelerate, de-risk, and scale services and business models with direct climate-resilient impacts for transformative adaptation. Hence, the insurance was bundled with climate-resilient seeds for smallholder adaptation, advisory based on climate and weather information, and a package of practices on agronomy, fertilizers, and water management. The model ensured that it is digitally enabled (using satellite data and mobile networks) and indicates the potential for scaling up digital platform-based bundled insurance products in the country.

4 Results and discussion

In this section, we present our main results, focusing on piloting bundled climate insurance solutions among smallholder farmers offered with drought-resistant crop varieties, weather index insurance, and crop advisories to evaluate the future scaling potential of bundled products.

4.1 Findings from the implementation of bundled insurance services

The scaling of the BICSA covering maize and rice farmers with the four components of the bundled solutions resulted in the provision of approximately 2,572,538.22 million rupees (USD 13,891) as compensation to eligible farmers based on the deficit and excess rainfall triggers across the pilot

TABLE 5 Role of different partners in the implementation of the bundled insurance.

Partners	Insurance industry	Seed Company	Weather advisory	Government agri research and extension
Contribution	• Insurance product • Pilot and business models • Coordination with government	• Seed production, marketing, and delivery • Coordination with research institutes and insurance Co.	• Agrometeorological advisory for individual farmers • Support in index insurance product and damage assessment	• Strengthening farmers' income and managing risks • Technology utilization and data • Village outreach and agricultural extension • Scaling up and institutional coordination • Workload distribution
Benefit	• Expansion of the agricultural sector • Build index insurance capacity • Build business relationship • De-risking through blended finance for premiums	• Increased product interest by farmers • Expansion of new areas • Build business relationship • Increase sales	• Increased product interest by farmers • Build business relationships across value chain partners • Client increase	• Farmers more protected from climate risks • De-risking fiscal deficit (disaster risk) through the inclusion of private partners
Impact	• Wider acceptance by farmers	• Strengthen agricultural producers against loss of crops from climate shocks	• Strengthen climate safety program against extreme events	• Building climate resilience in the agricultural sector

Source: Authors.

districts covering the 2021 *Yala* and 2021–2022 *Maha* seasons (Tables 6, 7). Our findings of comprehensive risk management are consistent with other case studies evaluated in India, Kenya and Zambia on the benefits of bundling with climate insurance products, such as weather-based insurance combined with agricultural inputs, which can significantly enhance resilience and reduce the vulnerability of farmers to climate-induced shocks (Mukherjee et al., 2017; Bulte et al., 2020). The study also demonstrates that bundling these solutions helps farmers make informed decisions based on weather forecasts and insurance coverage, leading to improved crop management and reduced climate risks.

In the 2021 *Yala* season, insurance was provided with a 2,500 LKR premium for all the districts, and at the end of the season, the farmers received insurance claims covering all the districts, but in the 2021–2022 *Maha* season, the farmers in Monaragala and Vavuniya districts did not receive the insurance claims because the area did not overcome the insurance triggers kept for both drought and flood disasters. The paddy seeds provided to the farmers during the 2021–2022 *Maha* season are BG 352, BG 300, BG 358, and AT 362. Hybrid Maize—JET 999 was provided as climate-resilient seeds. In terms of insurance claims received by farmers in both seasons, the maximum value of 2,651.17 LKR was received by the farmers of Vavuniya in the 2021 *Yala* season, while the farmers of Ampara received the minimum insurance claim of 850 LKR. However, it is evident that there has been significant insurance coverage for farmers in both seasons.

The above figure indicates that farmers' enrollment in the *Maha* season has gained momentum from the previous season (Figure 5). Farmer leaders informed that farmers enrolled in the previous season had received claims which induced other farmers to enroll in the following season. Following the implementation of the bundled insurance, feedback from the farmers enrolled in the program was collected to better understand the areas of improvement. Most of the farmers appreciated the initiation of the weather advisories as they depend on rain for cultivation (program implemented in intermediate and dry agro-climatic zones), and the forecasts had helped them in planning ahead. For example, one of the registered farmers in Monaragala district mentioned,

> "*…I had to harvest the groundnuts and was planning to pump water from a great distance because of the lack of rain. But according to the weather forecast you gave; it was said that it would rain in the coming days. So I delayed the harvest of the groundnuts for about 2 days. It actually rained as informed by the climate forecast. I did not need to pump water, so I was able to save a lot of money*" (20 April, 2021).
>
> Another farmer in Ampara district indicated, "*…We look forward to participating in your program during the Maha season. About 385 farmers in our village joined the Yala season program, and it would be great if they could be involved in the Maha season as well.*"

The farmers were of the view that weather advisories should increase the forecast period and the precision for improved decision-making process.

> "*…and it would be very good if you could give us information by increasing the forecast period. The weather forecast you provide is often correct, but as far as I can remember, there were times when it went wrong*" (a farmer from Ampara district, on 20 April 2021).
>
> "*…it would be great if we could increase the number of frames for next season…*" (a farmer from Kurunegala district, on 15 March 2021).
>
> "*…In my experience, I say weather and agricultural advice are really important for the success of cultivation. I think it would be better if I could provide weather forecast for more than 5 days*" (a farmer from Monaragala district, on 18 December 2021).

The farmers also mentioned that mobile services should improve as it is the medium to access the services in their respective areas. Farmers in Ampara stated, "*…we need a better telephone network. Otherwise, we will not receive the text messages you send…*" Along with network

TABLE 6 District-wise summary of farmer enrollment and insurance claim for the 2021 *Yala* season.

District	GND name	Number of farmers	Claim per farmer (LKR)	Total claim (LKR)
Vavuniya	Nainamadu	84	2,651.17	222,698.62
Kurunegala	Gajaneegama	214	1,462.49	312,971.79
Kurunegala	Panwewa	103	1,133.3	116,729.9
Kurunegala	Thisnampolagama	113	1,155.2	130,537.035
Anuradhapura	Hurulu Jayapura	85	1,870	158,950
Monaragala	Kolonwinna	34	870.05	29,581.53
Monaragala	Morawa	38	958.51	36,423.285
Monaragala	Veheragala	5	879.21	4,396.06
Ampara	Mahoya	645	850	548,250.00
Total		1,321		1,560,538.22

Source: Authors.

TABLE 7 District-wise summary of farmer enrollment and insurance claim for the 2021–2022 *Maha* season.

District	GND	Number of farmers	Premium (LKR)	Claim per farmer (LKR)	Total claim (LKR)
Vavuniya	Nainamadu	100	2,700	No claim	No claim
Kurunegala	Thisnampolagama	100	2,700	1,710	171,000
Anuradhapura	Horupothana	200	2,550	1,425	285,000
Anuradhapura	Ipologama	100	2,700	2,520	252,000
Monaragala	Kolonwinna	90	2,700	No claim	No claim
Monaragala	Morawa	120	2,550	No claim	No claim
Monaragala	Veheragala	90	2,550	No claim	No claim
Ampara	Tampitiya	200	2,550	1,520	304,000
Total		1,000			1,012,000

Source: Authors.

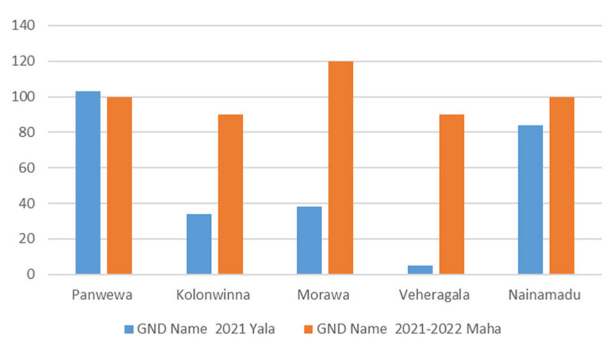

FIGURE 5
Increase in farmers' enrollment in different villages during the *Maha* season. Source: Authors.

improvement, proper enrollment was also cited as an essential consideration during the registration for the advisories. One of the farmers in Kurunegala district mentioned, "*…most farmers in our area have not received that advisory SMS.…*"

The enthusiasm from the farmers and the farmer leaders on the weather advisories and their feedback that the logistics of the registration and the mobile networks need improvement implies a potential uptake of the bundled insurance.

4.2 Scope for scaling: some proposed business concepts

Insurers and technical service providers[1] (TSP) are primary leaders of the index insurance value chain. In the insurer-led model, insurance companies provide the service. The insurer designs and underwrites the product. The insurer model can include partners such as aggregators[2]/mobile money providers

1 Companies that provide administrative and technical input for technical services which might include the insurer's responsibility of designing the insurance, with the exception of ensuring regulatory compliance and underwriting. This is primarily due to the reason that the TSPs lack insurance licenses.

2 An aggregator here refers to companies involved in agribusiness, seed manufacturing.

or TSPs. Aggregators are usually involved in targeting potential customers and marketing the service. TSPs are sometimes included in the partnership to provide specialist assistance in service design and monitoring the index trigger. Premium payments and claim payouts are carried out by aggregators either through cash-based collection or mobile money where available. In some cases, TSPs are well-equipped to design the product, but as they do not have insurance licenses, they require an insurance partner. TSP-led services target farmers directly or through distribution partners (such as mobile network-based operators (MNOs), input suppliers/aggregators, microfinance institutions (MFIs), and non-governmental organizations (NGOs).

One of the extensions suitable for scaling up these models is the inclusion of a "catalytic" micro-agent downstream of the value chain. The "farmer leaders" or farmers with more influence within the community can be considered for extending the service chain to the last mile. The uptake of agricultural insurance is arguably low due to different confounding factors like lack of awareness about insurance products, low financial literacy of the farmers, and low penetration of the insurance companies or other financial services in the rural areas. Even though farmers are aware of insurance, insufficient knowledge and understanding of financial services and their mechanisms imply that farmers might not immediately trust the service provider. For farmers aware of the insurance, the likeliness of using the insurance service increases with their understanding of the modality of the service and the value it provides. Traditionally, insurers take the help of insurance agents at the local level to reach the farmers. Using the *farmer leaders* within the community helps gain the trust of smallholder farmers and overcome the problem of lower financial literacy (Rosenstock et al., 2020). Accordingly, in such communities where influential farmers exist, training them with insurance products by the insurers for enrolling other farmers can be a strategy for scaling. The inclusion of these influential farmers in the business model can be increased through the identification of farmers willing to take up rural-level enterprises, and the leader of the value chain (insurer/TSP/MNO) needs to incentivize such operations by enrolling other farmers (Greatrex et al., 2015; Long et al., 2017; Prager et al., 2021). Over time and with the increasing expertise of such enterprises, delivery of bundled solutions can be included.

Compilation of different datasets through the digitized platform can be used for scaling up insurance utilizing different business models. One such example is the utilization of mobile-based technology for reaching customers. The MNO business model has gained prominence in many low- and middle-income countries. Apart from the insurer- or the TSP-led model, the MNO-led model is an emerging approach where the existing assets of the mobile company are used to reach the subscribed customers under the network. For example, Econet in Zimbabwe and Safaricom in Kenya are MNO-led insurances that use their assets to offer index insurance to farmers. Both these MNOs use their digital platforms to provide service to smallholder farmers. In this model, the technical functions (such as regulatory compliance, underwriting policy administration, index trigger monitoring, and claims management) usually remain with the insurer/TSP. This might hinder the MNO from leading the value chain, especially in situations where the insurance sector is not competitive, and there exists opportunities for insurance companies to grow their customer base and discontinue the contract (partnership with the MNO).

Utilizing MNOs to register and locate farmers and using mobile money to collect premiums and payout claims can be possible strategies for upscaling. Precise locations of farmers are critical to increase scalability and reduce basis risk for index insurance. Automating the collection of user locations through mobile networks (Global Positioning System) can overcome this challenge. In case automated service cannot be used, the mobile networks of insurance agents can be used for face-to-face registering of the users. For bundling insurance with climate and crop advisory services, mobile networks [usually through Unstructured Supplementary Service Data (USSD), Short Message Service (SMS), and Interactive Voice Response (IVR)] offer valuable opportunities. However, in MNO-led models, call center crop and climate advisories customized to the needs of the farmer (regarding special agro-climatic zones) can improve the demand for insurance products (Long et al., 2017; Groot et al., 2019; Prager et al., 2021). Additionally, such call centers can be targeted toward educating customers about the need for insurance, any disputes related to the insurance, and providing solutions on call for effective service delivery. Using digital platforms reduces the transaction costs for enrollment and has a huge potential in Sri Lanka. It has been estimated by Rambukwella et al. (2020) that in Sri Lanka, approximately a company spends LKR 20 on administration costs to earn a premium of LKR 100. Digital innovation for index insurance can reduce operation costs by 30% in Sri Lanka.

The scaling up of bundled insurance depends on different institutions playing different roles. The following Table 8 presents recommendations on the roles and responsibilities of different stakeholders.

The scaling program should have an approach that embeds targeted outreach, inclusivity, and capacity building of farmers. This would ensure that the program reaches smallholder farmers, women farmers, and marginalized communities often most vulnerable to climate impacts (Greatrex et al., 2015). Community leaders, agricultural extension agents, and farmers' organizations should be included in outreach campaigns to increase program awareness and participation. Similarly, the agricultural department, through the extension agents, should provide comprehensive training programs for farmers that encompass climate-smart agricultural practices, proper use of drought-resistant seeds, and understanding of index insurance. These training sessions should focus on sustainable farming techniques, efficient water management, and the benefits of using climate-resilient seeds.

5 Conclusion

Climate change induces more severe extreme weather events by altering the frequency, timing, intensity, and duration. Floods and droughts are the two most devastating consequences of the climate crisis, with a huge impact on agriculture. Smallholder farmers are most vulnerable and face a range of shocks and challenges beyond their control. These shocks have a drastic

TABLE 8 Main responsibilities of different institutions for the upscaling bundled insurance.

Recommendation	Responsibility	Description of roles
Climate/weather information	Meteorological department	Establishment of weather stations, utilization of earth observation data, and sharing of weather data with insurance companies to design a robust insurance
Index insurance customization	Insurance company (public or private entities)	Underwrite risk and design the insurance based on the principle of customization (specific needs and risks of the region.
Agro-advisory services	Insurance companies and mobile network companies	Disseminate weather and agronomic information through SMS alerts, mobile applications, or community radio to enable farmers to make informed decisions in real time.
Access to climate-resilient seeds	Seed companies and government agricultural research institutions	Ensure access to high-quality drought-resistant seeds suitable for the local climate conditions. The government can facilitate by subsidizing seeds to make them affordable for small-scale farmers.
Credit facilities linked to insurance	Bank and non-bank financial institutions	Provide credit-linked insurance to farmers
Multi-stakeholder partnerships	Aggregators	Foster partnerships between government agencies, NGOs, financial institutions, and private sector stakeholders to pool resources, share expertise, and support program implementation.
Data collection and analysis	Aggregators/insurance companies/agricultural department	Establish a robust data collection and analysis system to monitor the program's effectiveness and assess its impact on farmers' resilience, leading to evidence-based decision-making for further scaling

Source: Authors.

impact and affect their incomes and livelihoods. Extreme climate events are often coupled with unexpected agricultural events, such as market and price fluctuations or pest and disease infestations, and non-agricultural events, like health problems, increasing the helplessness of the smallholders. Catering to these challenges, national, regional, and local data must be integrated to build instruments that increase the preparedness for floods and droughts. Index-based agricultural insurance is one of the innovative approaches that integrate different information and is perceived to help tackle the challenges of extreme weather events. With the help of remote sensing, historical weather datasets, spatial maps of flooding extent, and socioeconomic data, hydrodynamic models can be prepared, indicating spatiotemporal variability of flood parameters. In addition to index insurance, bundling the insurance credit facilities, inputs (seeds, fertilizers), and crop and weather services is gaining importance as it provides holistic mitigation measures. The value addition through agronomic services, agricultural inputs (seeds, fertilizers), and credit helps smallholders and supports scaling up of the insurance services, reducing the associated risks of agriculture.

The present study based in Sri Lanka is an example of such an implementation of bundled insurance. The bundled insurance was implemented in five districts—Ampara, Anuradhapura, Monaragala, Kurunegala, and Vavuniya. Due to the increasing impact of climate change on crops in the dry zone of Sri Lanka, the dry zone was covered during the implementation and upscaling of the insurance products. The business model implemented is insurer-led, whereby seeds and climate advisory were bundled with the insurance product. The implementation included 1,321 farmers for the *Yala* season 2021 and 1,000 farmers for the *Maha* season 2021–2022, with approximately 30,000 weather advisories to the farmers during this period. Following the implementation of the bundled insurance, a follow-up on the assistance received by the farmers from the project was conducted. The feedback from the farmers indicated a willingness to take up bundled insurance in future. It has also been realized through the implementation that partnerships are crucial driving factors for the growth of index insurance. This includes insurers, TSPs, aggregators, extension agencies, agro-dealers, seed companies, and government agencies.

Based on this experience, the study recommends different mechanisms for scaling up the market for insurance products. This includes targeting farmers' uptake through community-based influential farmers willing to establish rural enterprises for enrolling farmers with insurance products. The index insurance value chain for agriculture requires the expertise of different agents in delivering the product. Insurers are required to design the product, regulatory compliance, and underwriting; TSPs provide data for designing and monitoring the trigger, and aggregators use their reach to farmers and cooperatives to promote and market the product. With digitization across the value chain, MNOs increasingly become potential competitors for upscaling bundled insurance. MNOs can locate farmers either through GPS location-based systems or through the use of mobile networks of rural agents registering farmers. Through MNOs, mobile cash is a facility that can be targeted for premium payment and claims settlement. The MNOs can also introduce call center facilities dedicated to weather and crop facilities and provide solutions on insurance premiums, claims, and related procedures. To sustain the process, it is envisioned that MNOs need to formulate business-to-business (B2B) partnerships to deliver index insurance services at scale as B2B allows sell of bundled value-added services.

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

GA conceptualized the study and contributed to overall project coordination. SG and NA provided technical backstopping on data analysis and imagery. GA, AT, and NA drafted the manuscript. GA was involved in funds sourcing and NA was involved in field activity arrangements. 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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Climate-smart agricultural practices among rural farmers in Masvingo district of Zimbabwe: perspectives on the mitigation strategies to drought and water scarcity for improved crop production

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Climate change is one of the most significant challenges many rural farmers face in sub-Saharan Africa, as most agricultural practices are rainfed dependent. Many of these rural farmers are small-scale farmers with limited access to financial assets, agricultural equipment, and inputs. With a rapidly changing climate and limited access to agricultural resources, many rural farmers in Zimbabwe have found it extremely difficult to engage in meaningful crop production activities and secure their livelihoods and incomes. This paper employs participatory research methods to examine adaptive strategies adopted by rural farmers. The strategies include optimal water resource utilisation, early maturing seed adoption, soil and water conservation (SWM), and nutrient management techniques (NMT). Cost-effective integration of labour and post-harvest storage facilities is also considered. Rural farmers, despite constraints, actively engage in these adaptive practices. The study assesses the effectiveness of initiatives to enhance crop production and build resilience against climate variability. Discussion centers on the comprehensiveness of these adaptive techniques within the broader framework of sustainable development goals, focusing on goals 1 (No Poverty) and 2 (Zero Hunger). The findings contribute to understanding and promoting resilience among vulnerable households facing climate-related challenges.

KEYWORDS

climate change, adaptation, livelihoods, crop production, climate-smart-agriculture

Introduction

In the context of climate change, poverty, and food insecurity in rural Zimbabwe (Brown et al., 2012; Muzari et al., 2014), farmers have demonstrated resilience by improving their ability to adapt to changing conditions through the adoption of climate-smart agricultural (CSA) practices (Brazier, 2017; Phiri et al., 2021).CSA is a globally recognised approach that enables farmers to address food and livelihood security issues while adapting to climate variations in an environmentally sustainable manner (Masipa, 2017; Brouziyne et al., 2023) with minimal greenhouse gas emissions (Kangogo et al., 2021). It takes a holistic approach to tackle the interconnected challenges of food security and climate change (Akzar and Amandaria, 2021; World Bank, 2023). Introduced by the Food and Agriculture Organization (FAO) in 2010, CSA gained rapid acceptance in many agricultural systems in Zimbabwe, particularly in Masvingo, where it aimed to alleviate the hardships faced by farmers dealing with elevated poverty rates, unemployment, increased crime rates, food insecurity, and nutritional deficiencies (Mango et al., 2014; ZIMSTAT, 2016; Zimbabwe Humanitarian Appeal Revision Report, 2020, 7). Success stories documented by Nyamangara et al. (2013); Mupaso et al. (2014), Hunter et al. (2020), and Phiri et al. (2021) emphasise how the adoption of CSA practices has improved farmers' prospects of securing income, essential for accessing critical services such as healthcare, education, food, transportation, and agricultural extension services, all crucial for their well-being.

However, the multifaceted nature of climate-smart agriculture (CSA) practices requires a more comprehensive understanding of farmers' perspectives and their appreciation of these strategies. While quantitative assessments have provided valuable insights into the outcomes and impacts of specific CSA practices, there is a significant gap in our understanding of farmers' experiences, feelings, beliefs, attitudes, and challenges in adopting CSA strategies. This gap is particularly pronounced in sub-Saharan Africa, where CSA adoption rates are relatively low compared to other regions, and the factors influencing adoption are unique (Kangogo et al., 2021). Moyo et al. (2017), Mutambara and Munodawafa (2014) and Makate et al. (2019), highlight that the low adoption rates can be ascribed to a range of challenges, high costs of raw materials with the reluctance to integrate CSA practices with proven effectiveness into existing agricultural systems, overreliance on donor funding for expanding CSA initiatives, inadequacies in both formal and informal information systems, such as weak extension services, and the absence of effective agricultural support policies and institutional strategies, including credit availability, property rights, and market institutions, among other obstacles observed in Malawi and Zimbabwe.

It is essential to acknowledge that CSA practices are not universally applied and that various local factors, including climate variability, resource availability, political and socio-economic conditions, technological access, and policy frameworks, influence their effectiveness (Shava et al., 2009; Rurinda et al., 2014; Moyo et al., 2017). Therefore, incorporating farmers' local knowledge and perspectives becomes crucial in developing practical and context-specific CSA strategies (Mubaya et al., 2012; Ogunyiola et al., 2022). Taking in to account farmers beliefs and attitudes in the design and implementation of CSA programs enhances their receptiveness and commitment to success.

To address this knowledge gap, qualitative research methods, such as in-depth interviews and focus group discussions, were employed to explore farmers' perceptions of CSA strategies, the benefits they perceive and the barriers they encounter. These qualitative approaches yield nuanced and rich data, providing valuable insights, potential solutions, and recommendations from the farmers.

Our study investigated the feelings, beliefs, attitudes, benefits, and challenges associated with CSA strategies among Zaka farmers in the Masvingo district. By delving into their experiences and perspectives, we aimed to shed light on the implications of CSA for adaptive capacity within rural households. Our findings can inform future policy decisions, ensuring that CSA programs are enhanced and tailored to meet the adaptive capacity needs of farmers. By doing so, we contribute to the broader agenda of achieving the United Nations Sustainable Development Goals, particularly in food security, poverty alleviation, and climate resilience. As CSA programs continue to evolve, prioritising farmers' perspectives and experiences becomes increasingly imperative in shaping the future of sustainable agriculture.

Materials and methods

Sampling and data collection

Zaka district encompasses 34 wards (Figure 1). This research aimed to identify and engage with small-scale farmers within these 34 wards. However, locating small-scale farmers across all 34 wards proved challenging, primarily due to outdated population records and restricted access to remote settings. Consequently, we adopted a strategic approach by enlisting the assistance of key informants to identify and locate small-scale farmers within the Zaka district. These key informants were selected from individuals with expertise in rural agricultural farming within Masvingo province, including academics, field experts, and government officers. It is important to note that Zimbabwean rural areas host various non-governmental and governmental organisations actively engaged in developmental projects to address poverty and food insecurity. Therefore, it was essential to engage with specialists within the Zaka district who had authority and were actively involved in the daily operations of rural communities.

One notable discovery during this research was the existence of the Zimbabwe Super Seeds (ZSS) private organisation. The selection of this organisation for inclusion in the study was intentional, as it played a pivotal role in delineating the wards actively involved in subsistence agriculture. ZSS had a well-established presence in addressing climate change- food-security related issues within the Zaka district and demonstrated a willingness to share their extensive knowledge on the subject. In pursuing this project, the study engaged in discussions with key personnel, including the project manager and field officer affiliated with ZSS, who provided valuable insights into identifying specific wards involved in subsistence agriculture. Zimbabwe Super Seeds is a private company that provides drought-resistant seeds and facilitates agricultural extension services and market access for small-scale farmers in Masvingo province.

The study found that ZSS manages 10 out of the 34 wards in the Zaka district. These 10 wards encompass rural farmers specialising in either dryland (rain-fed) or irrigated agriculture, and each ward comprises rural farmers engaged in distinct seed production activities. The 10 wards are numbered 1–6, 15, 16, 22, and 23. Wards 1–6 specialise in dryland farming, while 15, 16, 22, and 23 specialise in irrigation. The various seed projects undertaken in these wards encompass a range of crops, including maize (ZM309, ZM401, ZM521), sugar beans (NUA45, Gloria, Sweet Violet), cowpeas (CBC2, CBC3), sorghum (SV4), pearl millet (Okashana 1, PMV3), and groundnuts (ILanda). Among these crops, maize production held particular significance for this investigation, as maize is Zimbabwe's traditional food crop and a cornerstone of food and nutrition for numerous rural communities, contributing substantially to local food security. The study had access to four wards based on subject availability, specifically wards 1–3 and 15 (Figure 1). Wards 1–3 consist of dryland farmers and Ward 15 consists of irrigation farmers. All four wards specialise in maize seed production, as detailed in Table 1.

The number of farmers in Table 1 varies, and in order to obtain a representative sample of farmers from each ward while accounting for the differences between wards, the study applied a 30% margin of error, as indicated in Table 2.

Considering the data presented in Table 2, a stratified sampling approach was employed to ensure that the final sample accurately represented the entire population, notably when the population displayed multiple characteristics with proportionate disparities. Table 2 divides the population into distinct subunits based on the 30% margin of error, with these subunits serving as strata within the population. It is important to note that the representative samples drawn from each subunit possess characteristics consistent with the overall population.

The population in Table 1 comprises two distinct strata sets, one comprising dryland farmers and the other of irrigation farmers. The ratio between these two strata groups is set at 14:10, indicating that for every 14 dryland farmers in the overall population, there are 10 irrigation farmers. Recognising that dryland and irrigation farmers may have distinct experiences and characteristics, it was essential to ensure that both strata sets were adequately and proportionately represented in the final sample—consequently, the sample needed to mirror the same ratio as the population to be considered truly representative.

As these two strata sets are based on different farming practices, a larger sample was drawn from the irrigation farmers compared to the dryland farmers, as shown in Table 3. The study employed a systematic approach to select the sample from the farmers' contact list provided by ZSS. It involved using random sampling on the contact list with an interval of 10. For Wards 1–3, 10 individuals were randomly selected from the representative sample, totalling 30 dryland farmers in the study. In the case of Ward 15, an additional 20 individuals were added to the representative sample from the total number of farmers,

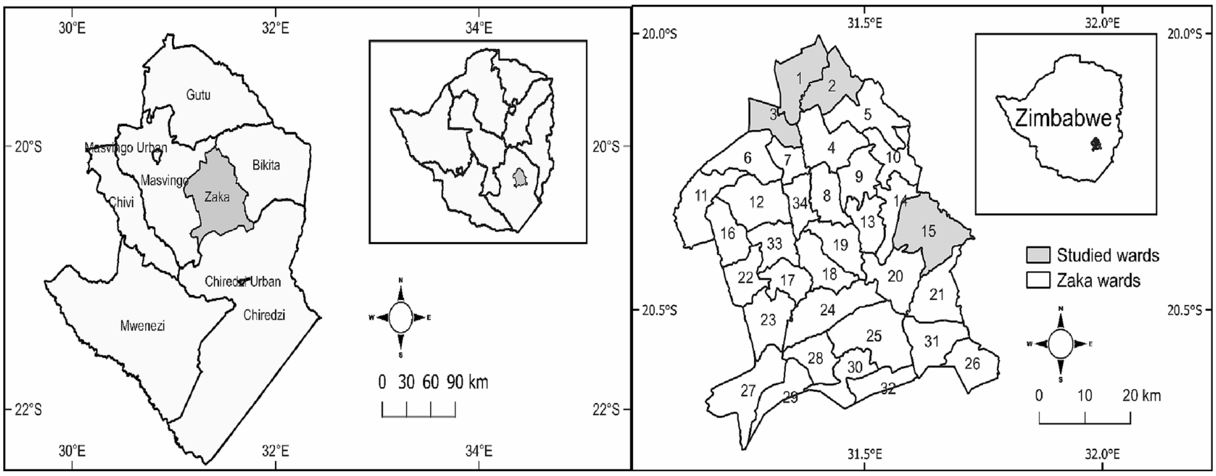

FIGURE 1
Map of Zaka district and location of wards 1–3 and 15. Source: Thandiwe Mpala.

TABLE 1 Zaka wards 1–3 and 15.

Wards	No of farmers	Type of farmers	Production specialty
1	67	Dryland	Maize
2	48	Dryland	Maize
3	28	Dryland	Maize
15	36	Irrigation	Maize

Source: Field Based Surveys (2019).

TABLE 2 Zaka representative samples.

Wards	No of farmers	Margin of error	Representative sample
1	67	±30%	20
2	48	±30%	14
3	28	±30%	8
15	36	±30%	10

Source: Field Based Surveys (2020).

TABLE 3 Acquired study population.

Wards	No of farmers	Margin of error	Representative sample	Final sample
1	67	±30%	20	10
2	48	±30%	14	10
3	28	±30%	8	10
15	36	±30%	10	30
			Total Sample	**60**

Source: Field Based Surveys (2020).

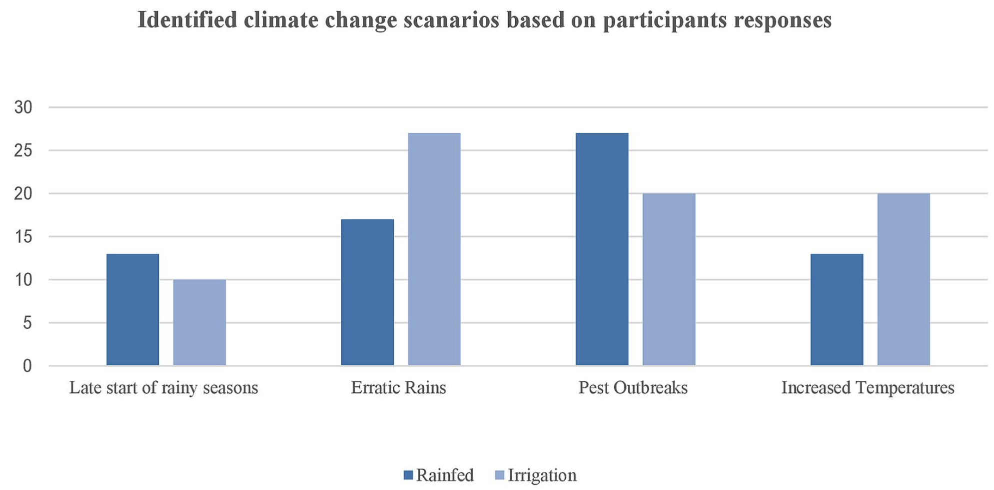

FIGURE 2
Identified climate change scenarios based on participants responses. Source: Field Based Surveys (2019).

constituting a group of 30 irrigation farmers in Table 3. This comprehensive approach resulted in a study population comprising 60 Zaka rural farmers, effectively ensuring a balanced representation of dryland and irrigation farmers within the research sample.

Traditional participatory approaches and analysis

The study employed traditional participatory approaches, which consisted of four focus group discussions that had 7–8 people with the dryland farmers and in-depth interviews with the irrigation farmers from the Zaka district in Masvingo, Zimbabwe. The data collection process commenced by transcribing raw data from interviews and focus group discussions. A thematic analysis which entailed systematically identifying codes within the transcribed data and classifying them into distinct thematic categories.

Results

Current climate change scenarios in Zaka district, Masvingo

The study commenced by engaging in discussions with the participants and key informants to gain insights into the prevailing climate change scenarios in Zaka District and to comprehend the Climate-Smart Agriculture (CSA) practices adopted by local farmers. Participants expressed that over the past 5 years, several climate-related factors significantly influenced their crop production (Figure 2). These factors included the outbreak of pests, erratic rainfall patterns, delayed onset of rainy seasons, and elevated temperatures. Notably, a majority of the interviewed participants perceived water scarcity as being closely intertwined with both the delayed onset of rainy seasons and erratic rainfall patterns. Other elements of drought, such as pest proliferation and increased temperatures, were also mentioned as indicators (Figure 2).

In the context of erratic rainfall, a substantial proportion of the participants, 57% of rain-fed and 90% of irrigation farmers reported experiencing this issue. Additionally, 33% of irrigation and 44% of rain-fed farmers raised concerns regarding prolonged rainy seasons. The participants underscored how untimely rainfall adversely affected their planning, leading to issues like water scarcity and crop losses, with rain-dependent farmers being notably affected (as detailed in Table 4). Approximately 13% of rain-fed and 20% of irrigation participants also acknowledged the impact of climate change through an increase in hot days over the past 3 years. These hot days were recognised to cause physical discomfort and crop damage, subsequently affecting agricultural productivity in Zaka. Moreover, pest outbreaks, notably the armyworm, were documented by 90% of rain-fed and 67% of irrigated farmers, damaging maize leaves and cobs.

Adopted CSA practices by Zaka farmers to enhance crop productivity in response to identified climate change scenarios

Soil and water management techniques

77% of irrigation and 80% of rain-fed farmers confirmed that they had received training in soil and water management (SWM) techniques (Figure 3). Additionally, 78% of the 60 rural farmers surveyed actively incorporated these techniques into their CSA strategies.

The participants' accounts provide insights into the substantial impact of SWM training on their perspectives, attitudes, and practical responses to the challenges associated with unpredictable rainfall patterns and rising temperatures. They underscored the significance of comprehending crop-specific attributes, such as growth rate, flowering and fruit set, nutrient requirements, temperature sensitivity, plant height, and soil moisture content, as pivotal factors contributing to improved crop yields.

Among the SWM techniques embraced by the participants were potholing, soil conservation, and water channelling. These strategies were acknowledged for their instrumental role in enhancing crop productivity. The participant feedback, presented in Table 5, reflects a range of positive experiences stemming from the tangible success they achieved with these techniques. Many participants reported meeting and surpassing their minimum yield expectations, resulting in increased income upon harvest.

As evident in Table 5, Participant 48 reported a noteworthy achievement, a 10% increase in crop yields over 5 years, primarily attributed to the dedicated adoption of the potholing technique. This technique involves the creation of small depressions in the soil, each measuring 15X15cm. The practice facilitates improved water retention and enhanced nutrient absorption, supporting sustained crop growth, particularly during dry periods. Similarly, Participant 28 experienced substantial enhancements in crop yields through the diligent implementation of soil management practices, which included water channelling and the preservation of soil fertility and moisture levels. It involved the mitigation of water losses in the soil due to evaporation and transpiration. These farmers were trained to construct ridges in their fields, thereby aiding water infiltration while simultaneously reducing evaporation.

These firsthand accounts from the participants underscore the pivotal roles of potholing and soil preservation tactics in promoting higher crop yields. They highlight the positive experiences and perceptions of the effectiveness of SWM techniques. Consequently, the responses in Table 5 underscore the critical importance of specific aspects of SWM techniques, such as potholing, water channelling, and soil fertility maintenance, in fostering sustainable and productive agricultural practices.

Drought resistant seeds

The results reveal a notable trend, with an approximate 90% adoption rate of drought-resistant seeds among irrigation and rainfed farmers (Figure 4). It is important to note that the adoption rate of DRS is high due to the support they receive from the organisation as indicated in Tables 6–8. The farmers can access to drought-resistant seeds without the need to source them elsewhere. However, it is important to note that the adoption rates of inputs are not similar for other categories of farmers in Zaka district as indicated by Participant 14 and 7 in Table 8. Communal farmers who are not affiliated with ZSS must consider the costs of acquiring drought-resistant seeds at retail prices, which may impact their adoption decisions. In contrast, farmers affiliated with ZSS are registered under the condition that they grow the seeds provided by the organisation, which incentivises their adoption of these specific germplasm seeds.

Despite the notion, the data strongly emphasises the widespread embrace of drought-resistant seeds as a crucial CSA strategy to enhance crop productivity in the face of recurring droughts, with 93% of the 60 participants actively incorporating these seeds into their farming practices (Figure 4). Participant 12 provided a vivid account of their personal experience, attesting to a doubling of grain yield, from 50 kg to 100 kg, achieved through utilising specific maize seed varieties renowned for their drought resistance (Table 7). Participant 16 confirmed these sentiments, underscoring the remarkable quality of these selected seeds: their minimal water requirements for crop growth, even under scorching climatic conditions. Participants highlighted a similar notion explaining the pivotal role of the attributes of drought-resistant seeds in effectively addressing challenges posed by drought. These attributes were characterised by early maturation, white semi-flint maize varieties with resistance to maize streak virus, exemplified by ZM309, ZM401, and ZM521 maize Drought-Resistant Seeds (DRS) (Table 6).

Participants consistently identified these attributes as the cornerstone of their CSA strategies for increasing crop yields during elevated temperatures and mitigating the inherent risks associated with crop failure (Table 7). We cross-referenced the responses with the project manager in 2020, it was confirmed that achieving a double yield increase, as mentioned by one of the participants, is not a typical or guaranteed outcome. The variability is attributed to dynamic climate conditions and economic challenges in Zimbabwe. Nevertheless, the project manager did emphasise that they consistently observe significant improvements in farmers' crop yields when using drought-resistant seeds compared to regular maize seeds. This enhancement is supported by crop productivity records (Figure 5), ultimately contributing to improved productivity and long-term income for farmers.

Survey records further substantiate the robust qualities of the maize seed varieties possessed by the participants, affirming their confidence in these seeds as invaluable tools for advancing agricultural productivity.

Nutrient management practices

The findings from focus group discussions and interviews revealed a substantial adoption of nutrient management practices (NMPs) among the participants. Specifically, 47% of irrigation and 53 percent of rainfed farmers actively incorporated NMPs into their agricultural practices to enhance crop yields (Figure 6). Overall, this highlights that 50% of the farmers acknowledged the significance of NMPs as a pivotal CSA strategy for safeguarding crop growth against the adverse impacts of drought (Figure 6).

The data presented in Table 9 provides valuable insights into the systematic and practical utilisation of fertilisers and pesticides, as reported by the participants. According to the data collected during the field survey, several critical aspects of Nutrient Management Practices (NMP) among Zaka farmers were revealed.

In the Masvingo region, farmers are distributed across agro-ecological regions 2, 3, and 4, a distribution primarily determined by

TABLE 4 Participants responses- identified climate change scenarios in Zaka district.

Respondents	Climate change indicators	Context	Responses
15	late start of the rainy seasons and erratic rains.	Experienced 2 years of erratic rains in the Zaka district and suffered from crop failure forthwith. She understood erratic rains and described seasons when rainfall was abundant or less. She further revealed that she struggled to plan her planting seasons to catch the rains and encountered challenges producing a good quality crop batch	*'It is challenging to plan the seasons when you are unsure how much rain you will receive. There are times when there is lots of rain, and then there are times when the rains are little. I have also experienced sometimes where there is no rain at all. All the other seasons in 2017 and 2018, the rainfall has been bringing water. The problem with rain is that my crops either get more or less. But in 2015 and 2016, rainfall was very erratic, and my crops did not do as well as I had anticipated.'*
18	Increased Temperatures	Complained about working in the fields during the hot days. He explained how he could see the crops change colour because of their sensitivity to high temperatures.	*'There are days where it is just too hot to work in the fields. I can see the heat affecting the crops because they change colour, from green to yellow or brown, and the leaves wither. When I walk on the ground, it will be hot.'*
9	Increased Temperatures	She explained that some of her crops did not make it to the harvesting stage because they dried up.	*'The weather changes. There are days where it pours a lot, and then they are days where it is humid and dry. I will look at the crops and find that they did not grow all the way. They just stayed at one stage because they were too dry to grow any further.'*
12	Pest Outbreaks	His crops suffered from the outbreak of pests. He had to discard the crops as they were not of the quality for production	*'During the hot days, there are a lot of pests that attack the crops. There are several seasons where I have had bad harvests because of pests. There is this fall armyworm that spreads and eats the crop. I find them on the leaves and inside the maize cobs'.*

Source: Field Based Surveys (2019).

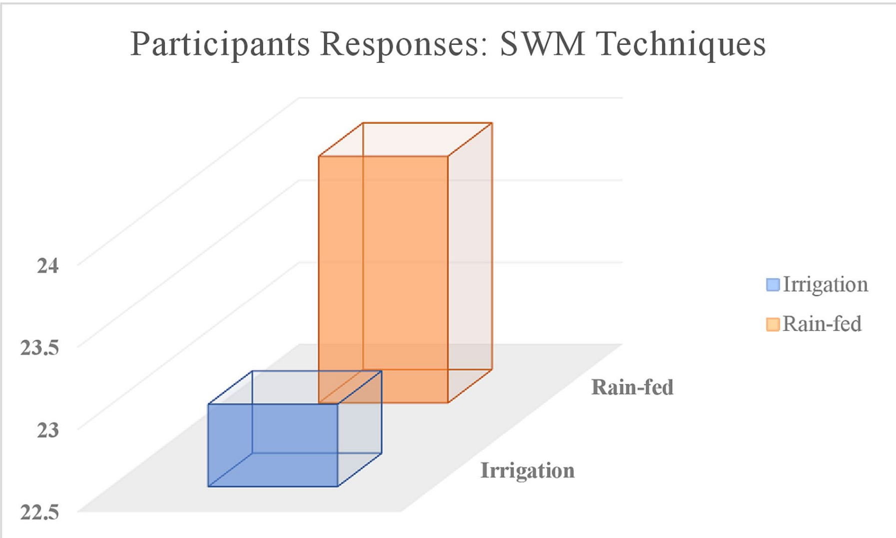

FIGURE 3
Soil and water management techniques responses. Source: Field Based Surveys (2019).

the local rainfall and water availability conditions. Lower regions tend to receive higher amounts of rainfall, while higher regions experience lower precipitation. The farmers interviewed predominantly reside in regions 3 and 4, with notably low annual rainfall averages, typically falling below 600 mm. Consequently, applying basal fertilisers and top-dressing practices exhibits variations within these regions.

For farmers in Wards 1, 2, and 3, the application of basal fertilisers is made at rates ranging from 250 to 350 kg/ha, along with top-dressing rates varying between 250 and 300 kg/ha for maize cultivation. In contrast, Ward 15, housing irrigation farmers, employs higher basal fertiliser rates within the range of 450-500 kg/ha, complemented by equivalent top-dressing rates. These disparities in application rates are

TABLE 5 Participants experiences with SWM techniques as a CSA strategy.

Participants	SWM themes	Responses
48	Potholing	*'With potholing, I create holes 15X15cm and dig and plant the seeds. Each hole will contain water, and it is kept within reach for the crop. But before I add water, I add all the fertiliser and manure into that hole as well. When it rains, the holes fill up with water. I have been doing this potholing for more the 5 years, and it has helped me maximise seeds produce, especially during these dry conditions. I have been getting good batches of seeds because of these methods. Like I used to produce 6,000 kg/ ha, now I produce 6,600 kg/ha of seeds. That extra 600 makes a huge difference when trying to make money.'*
27	Water Channelling	*'In the workshops, the company taught us how to use water efficiently to improve crop productivity by increasing infiltration and reducing evaporation. The field officer comes and shows us how to create ridges on the edges of our fields and in between. When water runs on a flat dry surface, it quickly dries up. We create ridges, and then the water is directed towards only the crops and reduces the rate at which the water would dry up. The technique works, and the crops come out well. I produce more than the minimum requirement. I always attend training; I learn something new that helps me do better as a farmer. I learn how to make more money with the seeds I have.'*
28	Soil Conservation	*'The training helped me perform better in my field. The organisation taught us in the workshops about crop and soil management. The people from the organisation and the trainers would train me in my field to teach me the proper way of actually doing cropping and how to maximise maize yields. They even showed me some demos on soil content and how to preserve moisture in the soil. It helped me get some good harvests because it meant that I would get a good sale at the market'.*

Source: Field Based Surveys (2020).

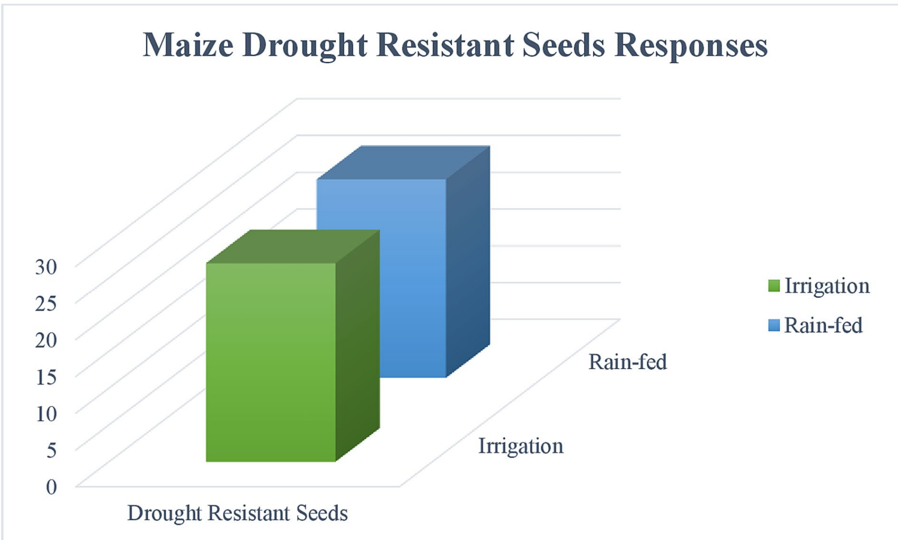

FIGURE 4
Maize. drought resistant seeds responses. Source: Field Based Surveys (2020).

TABLE 6 ZM309, ZM401 and ZM521 DRS seed characteristics.

Seed quality	Characteristics
Development Stage	Early Maturing – 110-120 days to mature at mid altitude and can mature up to 190 days in the hot lowlands of Zimbabwe.
Design	White semi-flint maize grained with high yield potential
Environment	Survive in drought prone areas
Disease resistance	Resistance to maize streak virus, grey leaf sport, cercosporazeae-maydis and common rust.
Yield Potential	5,000 kg/ha

Source: Field Based Surveys (2020).

contingent upon factors like soil nutrient content, the presence of potassium, nitrogen, and phosphorus in the soil, and the expected yield per hectare.

It is noteworthy that irrigation farmers are allocated 1.5 hectares due to access to water resources provided by ZINWA. On the other hand, rainfed farmers are allocated larger plots, covering 2 ha, to mitigate the risks associated with lower rainfall levels. Consequently, the yield per hectare differs, with Wards 1, 2, and 3 achieving approximately 6 tonnes per hectare and Ward 15 realising a higher yield of 12 tonnes per hectare. Soil characteristics also play a pivotal

TABLE 7 Participant responses-drought resistant seeds.

Participants	Drought resistant seed responses
22	*'The seeds are more advanced. The difference between normal maize seeds and these ones is that they can survive during the hot days. The normal ones may not survive for that long, but with these ones, they were designed to survive dry conditions for long periods and still produce good seeds.'*
12	*'These seeds carry a lot of good qualities that help me produce more in the fields. I have 1.5 ha of land. They give me 50 kg of seeds to go and plant. With this type of seed, I can make 100 kg of seeds from that one bag. The more seeds I produce, the more money I can make. These seeds do not take too long to grow and harvest'*
16	*'The seeds the organisation gave me are pretty strong for the hot conditions. They belong to the company. It is an advanced kind of seed. This kind of maize seed is suitable for this area. That is how some of the farmers have been able to produce and maximise production. Because in this area, it is challenging to grow regular seeds where the rains are erratic. However, with these kinds of seeds, they can survive with very little water in the hot conditions.'*

Source: Field Based Surveys (2020).

TABLE 8 Participants responses-affordability responses.

Participants	Agro-chemicals themes	Affordability responses
7	*Agrochemicals*	*'Getting pesticides and fertiliser is a challenge nowadays because of the economic situation in Zimbabwe. I go to the market, and there are people with different rates and prices. Today I find that one bag of 50 kg potassium nitrate is 1000RTGS (US$10), and then after* 2 days, *it will be now 1,500 RTGS (US$15). My friend told me the other day that other people were selling fertilisers at 2000 RTGS (US$20). It is not easy to decide which price to buy, mostly when money is also a challenge. So, I travel to other areas where it might be cheaper, but that is also expensive, but at the same time, I need the inputs.'*
14	*Agrochemicals*	*'It is a lot easier to get inputs from the organisation. They can supply it to me deduct it from the crop payment. I cannot buy these inputs with the rates they are charging. It is hard to find them at a fair price in the market. Most of the time I am given by the organisation, it is hard to locate them at the right price. it would be beneficial if the company could give the inputs all the time.'*
28	*Agrochemicals*	*'As soon as I get my money, I check for the prices of fertilisers, pesticides that same day, because I know the prices will not be the same the next day. I can only purchase the inputs when the money comes in. I buy for the season and prepare for the following year as well. I have to constantly be aware of the prices in the market, because if I wait, I will have bigger problems trying to buy them because of the price rates.'*
12	*Labour*	*'I hire people for the jobs, only if I have money or food to pay them.'*
9	*Labour*	*'Looking for people is slightly cheaper than buying a tractor. Although it would be nice to have a tractor, I cannot buy it on my own. That one would be a collective thing that all of us would pay for. But hiring people is easier because they are available, and all if I have to do, is meet them halfway with their wants.'*

Source: Field Based Surveys (2021).

role in fertiliser efficiency, with Wards 1, 2, 3, and 15 predominantly featuring white sandy loam soils. These soils facilitate more efficient nutrient absorption compared to clay soils found in other regions.

These farmers demonstrated a meticulous approach to implementing specific Nutrient Management Practices (NMPs), focusing on the precise application of agrochemicals tailored to the unique requirements of their crops. Their proactive stance was evident in the timely procurement of agrochemicals, ensuring a continuous and uninterrupted supply of essential nutrients throughout the dry season. Participants underscored the indispensable practice of soil quality assessment, commonly called soil testing, as an integral aspect of their agricultural activities during the growing season. This assessment allowed them to fine-tune crop nutrition to align with the specific needs of their crops.

Furthermore, participants shared insights into their engagement with Integrated Pest Management (IPM) strategies, encompassing selective pesticide use, crop rotation, biological controls, and meticulous record-keeping for each ploughing season. The knowledge and skills necessary for these practices were acquired through training provided by Zimbabwe Super Seeds (ZSS). The strategic utilisation of agrochemicals assumed paramount importance, enabling participants to effectively address.

Labour methodologies

The data reveals a deliberate adoption of labour methodologies by agricultural participants confronting the challenges posed by climate change scenarios. A detailed statistical analysis further highlights the significant adoption of these labour-strategies, with 60% of rain-fed and 47% of irrigation participants choosing to employ these methods to effectively manage the complexities of modern farming under the influence of climate-induced adversities (Figure 5).

The labour strategies, as explained, encompass a wide range of human and animal resources, including family members, friends, cattle, neighbours, and labourers within the community. Participant 40, a 58-year-old farmer with extensive experience, featured in Table 10, articulated his proactive approach during the focus group discussions. He actively sought hired labour to manage various essential tasks, such as weeding, crop clearing, and cattle management

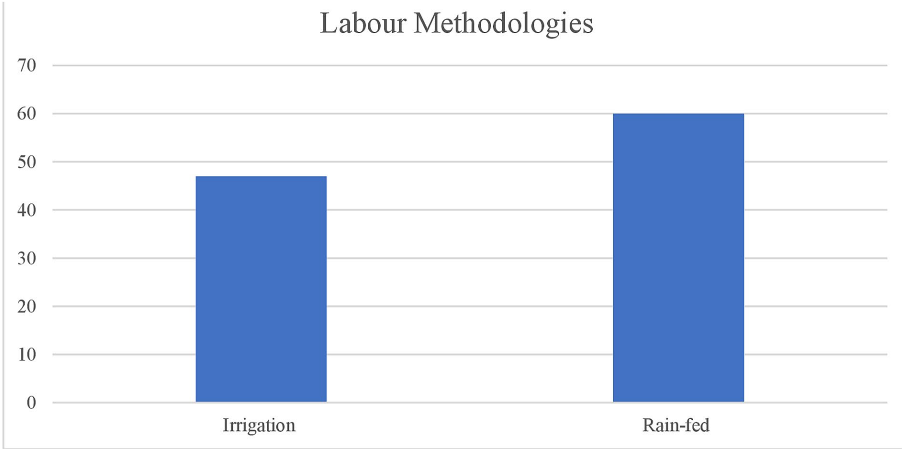

FIGURE 5
Labour Methodologies. Source: Field based Surveys 2020.

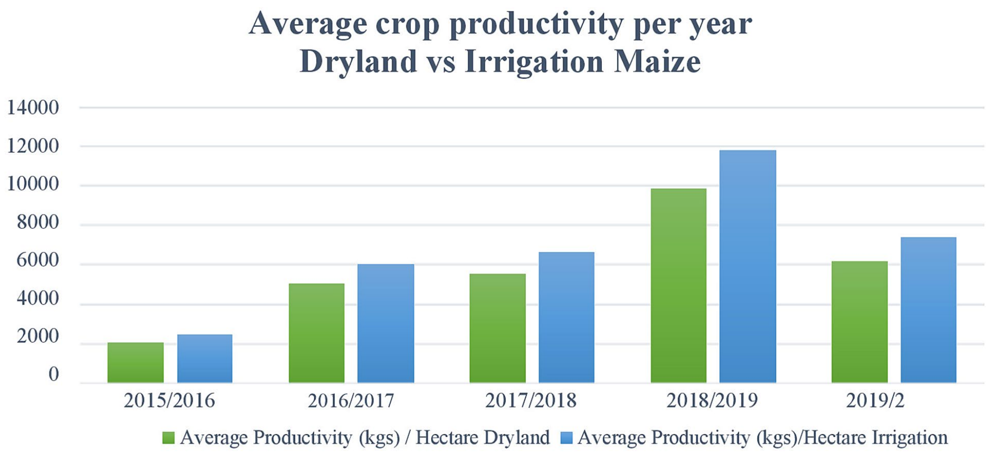

FIGURE 6
Crop productivity records per scheme: dryland vs. irrigation 2015–2020. Source: Zimbabwe Super Seeds (2020).

for cultivation and harvesting purposes. His account underscores the recruitment of local community individuals actively seeking employment opportunities and their integral roles in assisting with various farming activities, including weeding, seeding, cattle management, and row preparation. This strategic utilisation of external labour provided distinct advantages, enabling efficient task completion within a single day. As a show of reciprocity, he compensated these valuable contributors with items like food, seeds, and monetary payments, illustrating the symbiotic nature of these collaborative arrangements.

Participant 32, as shown in Table 10, shared insights into her family's central role in diligently covering essential groundwork whenever available. However, she also recognised the need to proactively engage labourers from her community to fulfil indispensable tasks when her family members were unavailable.

The detailed data in Table 10 collectively underscores the participants' astute recognition of the critical importance of additional labour in their complex agricultural endeavours. They effectively communicated their awareness that farming tasks, from intricate processes like maize planting to meticulous phases like harvesting and maize cob cleaning, often required a labour force that extended beyond the capacities of their immediate families. Consequently, they consistently expressed the need for external labour to facilitate the timely and efficient execution of these multifaceted tasks. This shared understanding holds profound implications, emphasising the pivotal role of labour productivity as an indispensable component in achieving optimal farm output. This significance is particularly pronounced in an agricultural landscape susceptible to the unpredictable influences of variable weather conditions.

Crop productivity records per scheme 2015–2020: dryland vs. irrigation

The bar graph compares the groups between the rainfed and irrigation scheme's crop production for 5 years from 2019 to 2020

TABLE 9 Participants responses-agrochemicals.

Participants	Agro-chemical responses
54	*'As a farmer, I need all the inputs for the crops to do well during the season. I need the water, the seeds, the cattle, the land, the fertiliser, and the chemicals. Especially fertiliser and chemicals are essential. I use fertiliser so that the crops get nutrients that make sure the crop survives nicely. I use pesticides to stop the spread of the pests attacking the crops. There are too many of them. I need to have at least the majority of the inputs to manage throughout the season. I have managed to recover some of the crops because of using fertiliser and pesticides.'*
6	*'During the hot days, I worry a lot about the maize in my fields, because sometimes when I check, I find plenty and plenty of makhonye (caterpillars) inside the cobs. I am still struggling to manage the spread—the damage shows on the maize leaves and inside the cobs. I would have no choice but to abandon them. So, I was advised by the field officer to use pesticides so that I could save more of my maize. The chemicals do help, but they are expensive. Fifteen litres of pesticide are 1,200 RTGS (12USD), and I would need three or four to manage the crops during the season. But using them helps me in making sure that my crops survive these pests.'*
37	*'Some of the farmers crops do not survive because they did not put enough fertiliser. I remember my neighbour coming to ask for some of my fertiliser because she did not have enough for the season and in the shops, they are expensive. Some of her crops died and some survived, but it was not her best performance in the fields. I am required to produce 3,500 kg of seeds and for me to do that I must have the inputs. Otherwise, I will produce lower than the standard that is required. So, having the inputs really help especially when rain is scarce. With the inputs I am able to produce above the required standard during the drought conditions.*

Source: Field Based Surveys (2021).

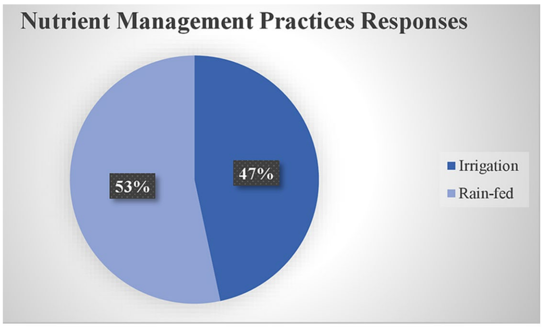

FIGURE 7
Nutrient Management Responses. Source: Field Based Surveys (2020).

(Figure 6). It is important to note that calculations were drawn on all the rainfed and irrigation schemes specialised in maize production under the Zimbabwe Super Seeds scheme. The data shows a gradual increase in crop productivity from 2015 to 2019 for both schemes and results from Tables 4–9 suggest that it is due to the participants adoption of CSA strategies. The lowest production levels were observed in the 2015–2016 and 2019–2020 periods, while the highest was in 2018 and 2019, while 2015 and 2016 were, respectively, observed as drought years. In comparing the two schemes the graph demonstrates that irrigation schemes outperformed rain-fed schemes in terms of crop productivity, whereas dryland yielded an average of 5039kgs per hectare. The results in Tables 4–9 and Figure 5 suggest that participants from Zaka district appreciate CSA practices as it has safeguarded them over the years from the risks of crop failures.

CSA limitations based on participant responses

The participants were asked what challenges they had experienced in applying CSA techniques. The findings indicated that the effectiveness of CSA strategies in enhancing crop productivity was significantly hindered by two main factors: affordability and limited financial infrastructure and limited diversification, as highlighted by maize cultivation, cash scarcity, agrochemicals, and labour (Figure 8).

Affordability and limited financial services

80% of the participants, rainfed and irrigation, expressed that hiring labour, applying agrochemicals, specifically pesticides and fertiliser was subject to price affordability (Figure 8). When participants could not afford the labourers price, agrochemicals, they struggled to enhance crop productivity. This was a serious limitation among the participants. Financial constraint is a critical factor in their decisions in Table 8 and it underscores the practicality of hiring labour and buying agrochemicals. They all expressed that CSA adoption strategies are ineffective if the raw materials come at a cost (Table 8). Responses suggest that the affordability of agrochemicals and labour plays an impact on the effectiveness of nutrient management strategies depending on the participants' income and price opportunity costs.

A substantial proportion of participants, amounting to 47%, highlighted the issue of limited access to financial services, while an additional 35 % underscored the challenge of limited diversification. The narratives provided by several participants shed light on the specific hardships associated with limited financial services in Zimbabwe, elucidating two primary obstacles that stand out prominently. Firstly, participants emphasised the geographical constraint of the central banking administration, which is predominantly located in Masvingo. This spatial concentration creates a significant obstacle for participants residing in outlying areas, as they must contend with the inconvenience and costs associated with travelling to access financial services. Secondly, the accessibility of funds within the banking establishments proved another formidable challenge. Participants revealed that the availability of funds was contingent upon the physical presence of cash within the banks. This condition hindered their ability to secure loans or make withdrawals when needed, impeding their capacity to allocate the requisite funds to implement their CSA strategies effectively in 2020 and 2021. For instance, in Table 11, Participant 12 candidly expressed the

TABLE 10 Participants responses-labour methodologies.

Participants	Labour methodologies responses
44 uses labour to plant and harvest on time	*'I pay for extra labour because I cannot do the fields by myself. I need people so that I can plant and harvest on time. I also need people to help me with cleaning the plants before it is sent for collection. If I do it by myself, it will take a long time. In a way, I am happy with other people helping my fields because I get to help other people who need jobs in our community. I get to help people who are hungry and unemployed and help me with my fields.'*
32 uses labour to cover groundwork needed for farming in replacement of family labour.	*'The family members help us in the fields. They are our labourers. But sometimes, it is tricky for our families to help because we still have young ones that go to school, some of us are old, and it is difficult to stay in the fields for long, especially on the days where it is too hot. So, we pay other people to come and help us in our fields, and it is a lot easier because I can cover a lot of the ground in 1 day.'*
53 uses hired labour. Because of family members are not always present. Takes on the supervisory role in their fields.	*'I manage the fields with my family. Sometimes, all the members are not always present. Some are at school, some are at other places, so when they are at home, they help me when they can. In those times, I also seek extra help from other people. I give them tasks to do on the fields, and then I supervise to make sure that it is being done correctly. That's what I have seen other farmers do as well.'*
Participant 40. Uses labour to complete farming tasks and assist the community with extra jobs in the process.	*'I look for people who can help me in the fields. There are people in this area that are constantly looking for jobs. They come to me asking for jobs, and sometimes I go looking for them. They help me with weeding, putting the seeds in, rearing the cattle, and creating the rows. Using labour helps a lot because I can cover many tasks on the ground in 1 day. I just give the people different tasks that will cover the fields. I pay them with anything with food, seeds, money, and they come and help me in my fields. These days in Zimbabwe, it is tough to get by, so I help where I can, and they help me in return.'*

Source: Field Based Surveys (2021).

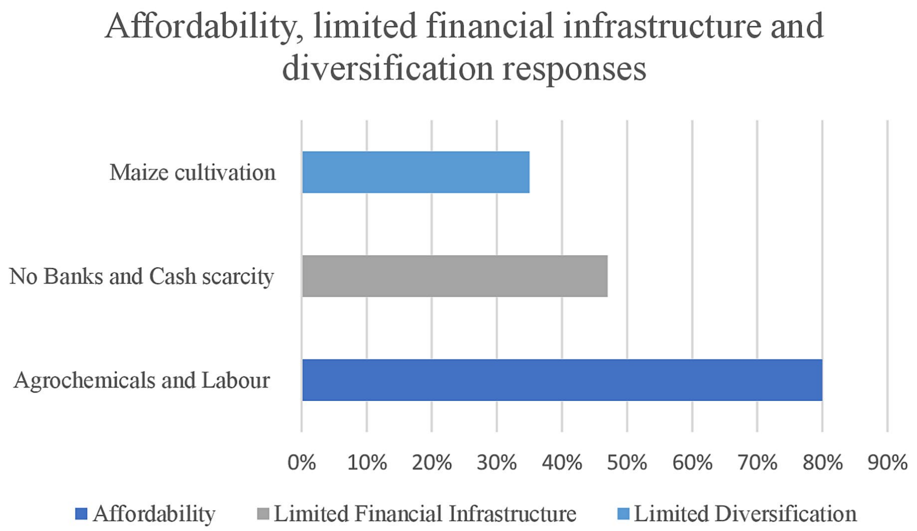

FIGURE 8
Participants responses: CSA limitations. Source: Field Based Surveys (2020).

difficulty of obtaining physical cash. Participant 28 further underscored the financial burden imposed by the geographical constraints. Participant 39 illuminated the scarcity of funds within the banking systems. These accounts in Table 11 collectively highlight the multifaceted challenges participants face in accessing financial opportunities critical for their agricultural activities. The constraints encompass the financial burden of travel, difficulties in securing loans, limited access to the required monetary sums, and the consequent inability to procure essential services promptly. These challenges significantly impede their pursuit of effective CSA strategies and underscore the pressing need for interventions that address the financial impediments hampering their agricultural endeavours.

Limited diversification

35% of participants reported limited diversification (Figure 8). Participants stated their fixed income was only maize production with Zimbabwe Super Seeds. For instance, in Table 11, Participant 48 said that growing other crops would improve their income-generating chances. Participant 32 reported a similar notion stating that growing livestock would increase their chances of survival if crop production were not always sufficient. The key result is that limited diversification limits their options for increasing CSA practices as they are restricted in benefits and thus subject to lower productivity and sustainability outcomes.

TABLE 11 Limited financial services and diversification.

Participants	Limited financial services and diversification themes	Responses
12	No banks and Cash Scarcity	*"Finding physical cash is a problem. The situation is that there is no money at the banks to apply for a loan or to even withdraw."*
28	Difficulty accessing the banks	*"I travel to the bank and find that the money has not been deposited. I have to decide if I will go back home and come back after 1 week or spend the day in Masvingo and try the bank the following day. It is expensive to travel. Masvingo is far."*
39	Cash Scarcity	*"There is no money in the banks, and at times the banks only give out specific amounts at a time. If I go to the bank, I can only withdraw 300RTGS a day. I have to come back the next day to withdraw the same amount until I have taken all my money out. I will not be able to pay or buy the things I need on that day."*
48	Seed Diversification	*'We asked the organisation if we could grow other crops on this site other than maize. At the market, they sell the crops at different rates, we could earn more money if we were growing different crops like maize, sorghum, and beans. It would increase our chances of survival'.*
32	Need to adopt livestock as a second alternative	*'There are many farmers here like me that specialise in breeding livestock because that is another way of making money. If ZSS could find us a livestock market, like they do for seeds, we could make more money for us and the organisation'.*

Source: Field Based Surveys (2021).

Discussion

CSA practices adopted by Zaka rural farmers in Masvingo

Soil water management techniques

Our comprehensive investigation into adopting CSA practices by Zaka rural farmers in Masvingo aligns with the established scholarly literature in the field. The incorporation of drought-tolerant crops, the application of soil and water harvesting based techniques, the different labour practices, and the adoption of nutrient management approaches have yielded positive outcomes, contributing to the development of adaptive farming systems that enhance productivity and safeguard the livelihoods of these committed farmers (Wauters et al., 2010; Girvetz et al., 2017; Makate, 2019).

The empirical insights extracted from the farmers' responses underscore the pivotal role played by soil and water management (SWM) techniques in shaping these adaptive farming systems and steadily enhancing productivity. Particular recognition is given to the practical utilisation of potholing and water channelling. Furthermore, the valuable training provided by Zimbabwe Super Seeds (ZSS) has emerged as a catalytic force, deepening farmers' understanding of CSA practices and equipping them with the knowledge and skills necessary for independent implementation. In the Zaka district, the training regimen covered essential techniques such as creating small 15x15cm depressions in the soil, judiciously integrating fertilisers, and adopting ridge formation along field edges and within fields. These interventions facilitated improved water filtration and nutrient absorption, resulting in noticeable yield increases (Figure 5). This outcome carries profound significance, extending beyond agricultural productivity, highlighting the multifaceted benefits of this process, including enhanced problem-solving skills, and increased personal fulfilment among the farmers, further underscoring the transformative potential of CSA strategies (Girvetz et al., 2017; Makate, 2019).

The efficacy of potholing and water channelling, often referred to as water harvesting in specific scholarly contexts (e.g., Ndlovu et al., 2020; Olabanji et al., 2020; Bagheri and Teymouri, 2022; Gebre et al., 2022), as integral components of CSA strategies has garnered considerable attention within the realms of climate change and agricultural discourse (e.g., Mavesere and Dzawanda, 2022). Potholing, a cornerstone of the farming approach known as *Pfumvudza* in Zimbabwe, has gained particular prominence in this discussion. This indigenous term encapsulates the conservation-oriented methodology embraced by rural farmers in Zimbabwe, emphasising its pivotal role in attaining elevated maize production levels and providing rural households with a sustainable source of food (Mavesere and Dzawanda, 2022).

The successful assimilation of Pfumvudza practices resonates profoundly with the experiences of the Zaka rural farmers, further corroborating these techniques' potency in propelling agricultural productivity and fortifying food security for Zimbabwe. These findings harmonise with the conclusions drawn from Mavesere and Dzawanda (2022) study, substantiating the pivotal import of potholing and water channelling within the larger CSA framework. These methodologies empower farmers to set their sights on bountiful crop yields while enhancing resilience to mitigate the adverse ramifications of drought and water scarcity.

The resounding adoption of these techniques among Zaka rural farmers underscores their immense potential and beckons towards a broader adoption that could unleash their transformative impact on rural livelihoods and galvanise food self-sufficiency initiatives.

Drought tolerant seeds

Our study's findings agree with the extensive research conducted by Cacho et al. (2020), who have strongly emphasised the critical role of adopting drought-resistant seeds as a vital adaptation strategy for vulnerable farmers in sub-Saharan Africa. This overarching objective is closely aligned with Sustainable Development Goal 2, which aims to end hunger, achieve food security, and promote sustainable agriculture worldwide. The adoption of drought-resistant seeds, as observed among Zaka farmers, represents a seemingly simple yet highly effective adaptation strategy. These farmers intelligently harness the inherent characteristics of such seeds, which include faster development, increased disease resistance, and an optimal growth environment for germplasm as highlighted in Table 6. Significantly, the efficacy of these seeds is further enhanced when no discernible issues related to taste, colour, and other plant attributes are encountered.

In line with these findings, the comprehensive research conducted by Habte et al. (2023) in Uganda provides additional support. Habte and colleagues' investigations shed light on the significant advantages offered to farmers who embrace drought-tolerant seeds, especially in maize cultivation. Their empirical evidence highlights that farmers who opt for drought-tolerant maize seeds achieve significantly better crop performance than those who stick with non-drought-tolerant varieties. Notably, their study revealed a 47% increase in yield for farmers adopting drought-tolerant seeds compared to their non-adopting counterparts, demonstrating the transformative potential of this adaptation strategy.

Our findings also align with those of Simtowe et al. (2019) regarding the benefits of drought-tolerant varieties in enhancing productivity, improving yield stability, and reducing risk exposure. Simtowe et al. (2019) found in their study in Uganda that adopting drought-tolerant maize varieties increased by 15% and reduced the probability of crop failure by 30%. These observations resonate with the narratives of Zaka rural farmers, exemplified by Participant 12, who shared a compelling account of a twofold increase in grain yield, surging from 50 kg to 100 kg (Table 7). The progress was inherently entwined with the distinctive qualities of the adopted seeds, including their early maturation (110–120 days), resilience to drought-prone environments, and resistance to the pernicious maize streak virus, as meticulously documented in Table 6. These attributes collectively contribute to the marked enhancement of crop yields and the concomitant reduction in susceptibility to drought-induced crop failures. The tangible outcomes of this adoption extend well beyond agricultural productivity, profoundly impacting food security and the welfare status of maize-dependent households. The amplified yields (Figure 6) translate into improved crop income and a surplus of marketable produce, thereby tangibly elevating these farming communities' overall well-being and economic resilience.

It is important to note that the success of increased crop yields and adoption rates of drought-tolerant maize (DTM) varieties vary across African regions. For instance, Simtowe et al. (2019) emphasise that it is not just about knowing about different crop varieties but also about having access to these seeds at an affordable price. Households that perceive these seeds as unaffordable are less likely to adopt the desired variety, even if they know the potential benefits it can bring to their production (Simtowe et al., 2019). Martey et al. (2020) indicate that adoption is significantly influenced by factors such as extension services, labour availability, and the location of farm households. Their findings show that the adoption of drought-tolerant maize has a positive impact on yields and commercialisation intensity, resulting in a substantial increase in crop yields (e.g., an increase of over 150% to 936 kg/ha for farm households that adopted DTM). It aligns with our research, which recorded a high adoption rate of 90% among Zaka farmers.

The high adoption rates observed among Zaka farmers can be attributed to the direct access provided by Zimbabwe Super Seeds (ZSS) as part of their contractual agreement highlighted by Participant 16 in Table 7. This observation agrees with the findings of Simtowe et al. (2019) and Martey et al. (2020), emphasising that such high adoption rates underscore the need for policymakers and development practitioners to encourage more farmers in to the adoption of DTM and promote research and the adoption of Climate-Smart Agriculture (CSA) strategies to enhance overall welfare and crop yields.

Furthermore, the literature provides additional evidence of similar findings from authors such as Fisher et al. (2015) and Igbatayo (2022). Our findings echo the broader consensus in the scholarly domain, affirming the paramount significance of adopting drought-resistant seeds as a linchpin in pursuing agricultural sustainability, food security, and the ultimate realisation of developmental aspirations in sub-Saharan Africa.

Nutrient management practices

Our study examined two groups of farmers: those practising irrigation (47%) and those reliant on rain-fed farming (53%; Figure 7). Despite this heterogeneity, a consensus prevails, underscoring the judicious and cost-effective utilisation of fertilisers and pesticides as indispensable strategies for enhancing crop yields. This perspective finds resonance with the research conducted by Jariwala et al. (2022), which accentuates the pivotal role of targeted fertiliser application in achieving augmented yields. Importantly, Zaka's farmers are not passive recipients of agrochemicals; instead, they approach their farming practices proactively. Their meticulous planning ensures that essential nutrients are consistently supplied to their maize fields throughout the extended dry season, thanks to precise timing and specific techniques tailored to different crops.

Furthermore, other studies, such as Larson and Frisvold (1996) and Pasley et al. (2019), have demonstrated that increased fertiliser usage can lead to moderate yet significant improvements in yield. Sub-Saharan Africa faces the challenge of raising the average fertiliser application rate from 10 kg/ha to 50 kg/ha within a decade to prevent soil nutrient depletion, equivalent to an annual growth rate of 18% (Pasley et al., 2019). Excessive fertiliser use and associated environmental concerns are not widespread issues in this region (Larson and Frisvold, 1996). The farmers under study, who predominantly belong to the category of small-scale farmers, already operate with limited resources, including a scarcity of livestock to generate inorganic manure, a valuable resource for sustainable agriculture, and given their resource constraints, these small-scale farmers are compelled to rely on agrochemicals to meet their productivity targets. While the ideal approach may involve a more substantial utilisation of inorganic fertilisers, the economic and logistical realities these farmers face necessitate a pragmatic reliance on agrochemicals to bridge the productivity gap.

The primary obstacles lie in ensuring the availability of fertilisers to farmers in the correct quantity and packaging and at the appropriate times. Several studies emphasise that the simple accessibility of fertilisers to farmers, in suitable quantities, packaging, and timing, remains a primary constraint in augmenting fertiliser use in sub-Saharan Africa (Larson and Frisvold, 1996).

The impact of training and formal education on farmers' proficiency in using agrochemicals is significant. There is a noticeable link between farmers who are more active in seeking training and their ability to use agrochemicals effectively. This aligns with the consensus in the academic community, supported by the research of

Abdollahzadeh et al. (2015), Cen et al. (2020), and Kouhouyiwo and Marcel (2022). These studies emphasise that farmers who are trained in application widely recognise the potential of agrochemicals to improve their farming. Based on the farmer's beliefs and attitudes, agrochemicals are seen as tools to enhance soil fertility and the overall quality of their crops, and farmers are committed to cost-effective practices, showing their practical and intelligent approach to farming optimisation.

Labour methodologies

Our findings align with Kangogo et al. (2021) research, highlighting the significant contribution of labour methods to crop productivity. In the context of small-scale farming, where efficiency is crucial, our respondents in Table 10 displayed a strong awareness of the essential role of labour in agriculture. Farming tasks, from planting to harvesting and cleaning, often require more hands than their immediate families can provide. This situation leads to a resource challenge, as family members may not always be available due to school attendance and age-related limitations. To address this labour gap and achieve their crop productivity goals, respondents often hire external labour. This practical response underscores the farmers' commitment to timeliness and efficiency in farming, especially in unpredictable weather conditions.

Moreover, a community-oriented dimension is evident in their labour practices, reflecting the findings in FAO's report (FAO, 2015). While pursuing their crop productivity goals, farmers also provide employment opportunities and act as a social safety net for fellow community members facing unemployment and food insecurity. This dual role demonstrates a deep sense of social responsibility and mutual support, going beyond self-interest and aligning with Murray et al.'s (2016) findings. As respondents engage in extra labour, they take on supervisory roles, contributing to knowledge transfer and quality control in their agricultural practices. This subtle aspect underscores their commitment not only to achieving optimal crop productivity but also to promoting a community responsibility of service and precision.

In summary, the insights from Table 10 provide a multi-dimensional understanding of the interplay between labour dynamics, family structures, community engagement, and agricultural efficiency in small-scale farming. These findings are consistent with Cock et al. (2022) research, emphasising the importance of enhancing labour productivity among farmers. The implications extend to crop yields, community development, and broader socio-economic well-being. Based on these insights, it is evident that rural development policies should prioritise improving labour productivity while also ensuring increased crop yields (Cock et al., 2022).

CSA limitations

Affordability and limited financial services

Our study's findings corroborate with research conducted by Zondo (2020), which underscores the pivotal dimension of affordability within the agricultural landscape. Our survey data, presented in Tables 8, 11, highlights insights gathered from Zaka farmers, unveiling the intricate interplay between agrochemicals and the farmers' socio-economic status. These observations echo the findings of GRAIN and IATP (2022) and Mpandeli and Maponya (2014), who recognised a discernible correlation between socio-economic status and the accessibility of agrochemicals and labour. It becomes evident that farmers with higher socio-economic status navigate the terrain of affordability more efficiently while their counterparts with more limited financial means grapple with the daunting spectre of financial constraints.

Table 8 underscores the significant financial burden posed by the cost of fertilisers on small-scale farmers with limited resources. This finding aligns with the insights provided by FAO (2015), which emphasise that restricted access to essential farming inputs, including fertilisers, hinders the aspirations of smallholder farmers, making their production goals challenging to achieve. In Zimbabwe, hyperinflation, as documented by Makochekanwa (2007) and Southall (2017), strongly influences the pricing of agricultural resources. This economic instability adds to the difficulties faced by farmers when buying fertilisers, given fluctuating exchange rates and economic uncertainties. The cost of agrochemicals is crucial, impacting farmers' ability to practice CSA effectively. Affordability is essential for accessing farming inputs, reflecting the financial capabilities of farmers for investing in agricultural operations. However, when pricing fluctuations and limited financial resources compromise affordability, it undermines the overall effectiveness of CSA strategies.

The accessibility and affordability of agrochemicals and labour are crucial for enhancing crop productivity and implementing sustainable farming practices. In the interplay of accessibility, affordability, and agricultural goals, we see the crucible where farmers' aspirations are forged, revealing their strong commitment to sustainable farming practices.

Regarding limited financial services, the findings from Figure 8, with 47% of respondents reporting a lack of access to finance, line up with the research of Lemessa and Gemechu (2016). Their work highlights the significant challenges arising from financial constraints in rural households, hindering both productivity and income growth. The farmers express two key challenges: limited access to finance due to the scarcity of financial services in their area and the lack of liquidity within banks. These findings are consistent with the research conducted by Parlasca et al. (2022), emphasising the profound impact of limited financial opportunities on farmers' capacity to explore economic opportunities vital for meeting their financial commitments.

Farmers require easy access to financial resources, including loans, credit facilities, mobile banking services, and savings, to navigate the unpredictable challenges of climate-related changes. These financial tools are essential for effective planning and preparation for future challenges, providing resilience in unpredictable climate variations. However, the data reveals additional challenges Zaka farmers face, such as the need for more financial infrastructure and financial resources in their area. Direct and indirect costs, like travelling to distant banks, are compounded by the scarcity of physical cash. These challenges limit their ability to explore alternative financial options, including loans and credit facilities, and hinder their capacity to obtain essential goods and services needed for their CSA strategies.

Limited diversification

When we focus on the responses related to diversification, as shown in Figure 8, we observe that these narratives align with the findings reported by Waha et al. (2018). Waha and his colleagues' research effectively explains the limitations imposed by restricted diversification practices among farmers. They state that this limitation hinders farmers' ability to increase crop production and adapt to changing circumstances. According to their research, this outcome not only highlights a significant challenge within the context of CSA for small-scale farmers but also provides valuable insights into its economic dimension.

In this context, the participants' heavy reliance on maize cultivation, facilitated by Zimbabwe Super Seeds (ZSS), stands out as a vulnerability due to their economic dependence on a single crop. Diversifying their range of crops emerges as a practical strategy to mitigate risks associated with climate change, offering stability in income and better competitiveness in markets that seek diverse, high-yielding crops. While maize is crucial for food security, diversification helps manage risks in crop cultivation.

It is important to note that diversification should extend beyond crop variety to include broader aspects such as production and socio-economic considerations (van Zonneveld et al., 2020). This comprehensive approach reduces vulnerability to price fluctuations and shields financial well-being from shocks. Participants actively participate in diversification, as seen in Participant 48's proposal to cultivate various crops for diverse markets and Participant 32's consideration of livestock breeding as an alternative income source, showing their intent to address production cost challenges in Table 11.

While the results do not definitively determine the outcomes of diversification, they highlight the participants' determination to overcome obstacles. Their commitment to navigating the complexities of agricultural production, focusing on survival and sustainable prosperity, is rooted in a keen understanding of risk.

Important tools required for effective CSA programs in Zaka district

Our alignment with the perspective of the World Bank (2017) and FAO (2022) is rooted in the notion that integrating research, development, advocacy, and training plays a pivotal role in effectively implementing climate-smart agriculture (CSA) programs for small-scale farmers. These comprehensive approaches encompass various components essential for the success of CSA initiatives. Germplasm selection, which includes breeding, introduction, and the multiplication of drought-tolerant crops, is a fundamental element of CSA. This process ensures that farmers have access to affordable and accessible resilient plant varieties capable of withstanding the challenges of changing climatic conditions, forming the foundation for bolstering agricultural resilience.

Within the CSA framework, the diversification of crop production emerges as another pivotal strategy, as supported by the field survey data and the World Bank (2017, 9). This approach encourages farmers to cultivate a diverse array of crops and engage in the raising of various crop species. Diversification serves as a risk-mitigation tool, reducing farmers' vulnerability to the adverse impacts of climate variability. It also enhances food security while positively influencing household incomes and nutrition.

Promoting organic farming practices is in alignment with principles of sustainability and environmental stewardship. Organic farming minimises the use of synthetic chemicals, emphasising natural methods for pest control and enhancing soil fertility. By advocating for organic farming within CSA programs, farmers not only contribute to reducing the environmental footprint but also enhance the long-term health and resilience of their agricultural systems.

Water harvesting and efficient irrigation methods, especially water channelling and potholing, are vital adaptation practices that significantly benefit small-scale farmers (e.g., Ndlovu et al., 2020; Olabanji et al., 2020; Gebre et al., 2022). These techniques facilitate the conservation of water resources, ensuring that crops receive adequate moisture, particularly during seasons prone to recurrent drought conditions, such as summer crops like maize. Improved irrigation and water management practices can lead to increased agricultural productivity, income, and improved nutrition for farming communities.

Soil management-based practices encompass a range of strategies to optimise soil health and fertility. These include precise fertiliser application, microdosing, manure application, crop rotations, and intercropping. Additionally, implementing soil conservation structures, such as controlling the velocity of surface runoff, is critical in preventing soil erosion and maintaining soil health. Healthy soils serve as the foundation of sustainable agriculture and are indispensable for ensuring the long-term success of CSA initiatives.

Conclusion

In summary, this study underscores the increasing imperative of climate-smart agriculture (CSA) practices for rural farmers, particularly in Zimbabwe, where recurrent droughts are becoming a pressing concern. As climate change intensifies, these extreme weather events are projected to become more frequent and potentially annual occurrences, posing an existential threat to agricultural productivity and, by extension, the quality of rural livelihoods. Rural farmers must fortify their crops against these formidable challenges by embracing CSA practices. This endeavour can be facilitated through sustained investments in training and research, fostering a culture of continuous improvement and adaptation.

The long-term nature of the benefits associated with CSA practices necessitates consistent and substantial funding and resources to expand and advance CSA programs tailored to the needs of small-scale rural farmers. While these farmers inherently appreciate the value of CSA practices, they require ongoing technological and technical support to sustain them independently. Consequently, this study leads to three key policy considerations.

Firstly, policymakers must allocate funding for developing and implementing comprehensive training programs to enhance farmers' awareness and receptiveness to CSA practices, focusing on rainfed farmers at increased risk. Secondly, there is a pressing need to underscore the importance of incorporating farmers' perspectives into climate change policies, ensuring that CSA programs align with the unique needs and socio-economic circumstances of the agricultural communities they seek to empower. This participatory approach will engender greater ownership and efficacy of CSA initiatives.

Lastly, policymakers should prioritise making drought-resistant seeds (DRS) accessible and available to every small-scale communal farmer dependent on farming for their livelihood. This step will significantly improve food security, increase farmers' chances of improving yields, and provide sustainable income for daily household needs. The advancement of CSA programs across Africa is significant in fortifying rural farmers' future income and food security. These programs serve as critical tools for enhancing farmers' adaptive capacity and resilience in the face of extreme weather events. By bolstering agricultural systems and securing sustainable livelihoods, these policy considerations resonate deeply with the broader global agenda, as articulated in the United Nations' Sustainable Development Goals (SDGs). They intersect with SDG1 (eradicating poverty), SDG2 (eliminating hunger), SDG12 (sustainable production), and SDG13 (climate action). These considerations become indispensable guideposts for steering agricultural systems towards a more resilient and sustainable future that safeguards the well-being of those on the frontlines of national and regional food production and security.

Limitations of the study

This paper primarily relies on data collected from Zaka rural farmers employed by Zimbabwe Super Seeds from 2019 to 2021. The results are grounded in the themes extracted from the farmers' responses.

The findings offer valuable insights, and a quantitative study could have been more suitable for comparison. It is imperative to recognise that the data collected within this timeframe may have limited generalisability beyond the regional context. The study sample intentionally excluded small-scale communal farmers, and farmers engaged in livestock breeding who were not affiliated with Zimbabwe Super Seeds. Although our initial objective was to conduct interviews with a total of 60 farmers, it became challenging to achieve this target due to the constraints posed by the COVID-19 lockdown restrictions. Despite these obstacles, we conducted interviews successfully and focus group discussions with many farmers, which still provided valuable insights and data for our study.

Furthermore, specific economic indicators, such as prices, mentioned in the findings are pertinent to the economic conditions prevailing in 2020 and 2021. It is essential to acknowledge that the dynamic economic landscape in Zimbabwe may have influenced changes in these indicators during that period. However, the information derived from this study provides valuable insights into the perceptions of local farmers regarding the efficacy of climate-smart-agriculture (CSA) strategies in enhancing crop productivity. By grasping the local perspectives, practitioners and institutions can gain a deeper understanding of farmers beliefs and attitudes and the diverse approaches farmers employ in adopting CSA strategies and the challenges they face. The study's findings contribute to the broader understanding of farmers' attitudes towards CSA strategies and shed light on the nuanced landscape of CSA adoption in the region.

Data availability statement

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

Ethics statement

The research involving human participants underwent review and approval by The University of the Witwatersrand Ethics Committee, resulting in the issuance of an Ethics Clearance Certificate. All participants provided written informed consent to participate in the study.

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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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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Selection of extra-early white quality protein maize (*Zea mays* L.) inbred lines for drought and low soil nitrogen resilient hybrid production

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In West and Central Africa (WCA), drought and low soil nitrogen (low N) impede increased maize (*Zea mays* L.) productivity and production. Due to climate change, the two stresses usually occur together, leading to food, nutritional, and economic insecurity in the sub-region. There is, therefore, the need for the development and availability of high-yielding extra-early maturing white Quality Protein Maize (QPM) synthetics and hybrids with resilience to the prevailing stresses through the identification of superior climate smart (extra-early maturing) QPM inbreds under stress (drought and low soil N) conditions. The study was conducted to identify stress-resilient QPM inbred lines for hybrid production and assess the association between grain yield and other studied characters. During the 2012 minor and major rainy seasons, 96 extra-early white QPM inbreds and four (4) normal endosperm maize inbred checks were assessed in multi-location trials under stress and optimal conditions in Nigeria. The experiments were laid out in a 10 × 10 simple lattice design with two replications. Data were recorded on grain yield and other agronomic traits. Significant variations ($p < 0.01$) were detected among the inbred lines for measured characters, indicating adequate genetic variability among the inbreds to allow for selection and improvement of grain yield and other measured traits. Grain yield was interrelated with all the traits used in the selection index. Moderate to high estimates of heritability were observed for most of the measured traits under stress conditions, indicating that the traits could be easily transmitted to the progenies. Fifty-seven out of the 96 QPM inbreds evaluated exhibited varying degrees of resilience to drought and low N. The QPM inbreds with desired traits may be used as genetic resources for the incorporation of tolerance genes into QPM populations in the tropics, as well as for the development of drought and low N resilient synthetics and hybrids in WCA.

KEYWORDS

climate change, drought, indirect selection for high yield, low soil nitrogen, quality protein maize, stress resilient maize

1 Introduction

Maize is an important staple crop for about half of the human population in sub-Saharan Africa (SSA). Due to its economic importance, it is anticipated to become the most important cereal crop by 2025 across the world (FAOSTAT, 2017; Bhadmus et al., 2021). However, factors such as drought and low soil N severely hamper its productivity and production across the sub-region, thereby increasing food and nutritional insecurity (Badu-Apraku et al., 2011; Annor and Badu-Apraku, 2016; Kountche et al., 2019).

The current poor maize grain yield of 2.01 t ha^{-1} in SSA compared to the global estimate of 5.75 t ha^{-1} (FAOSTAT, 2020) is caused largely by low soil N and drought. Due to climate change and farmers' inability to afford adequate quantities of fertilizers, the effects of the two stresses are very severe under farmers' field conditions in SSA (Annor and Badu-Apraku, 2016; Ertiro et al., 2017).

Maize reaction to low soil nitrogen and drought is controlled by similar mechanisms (Badu-Apraku et al., 2012a,b; Obeng-Bio et al., 2019), and the two stresses frequently occur jointly in farmers' fields (Kim and Adetimirin, 1997; Badu-Apraku et al., 2011; Ertiro et al., 2017). Separately, drought and low N can cause grain output reduction of 40–50% (Wolfe et al., 1988; Amegbor et al., 2017; Annor et al., 2019) and 30–90% (Menkir and Akintunde, 2001; Annor et al., 2019), respectively. When these stresses occur jointly and the cultivated varieties are vulnerable, the combined effect could be a total (100%) grain yield loss (Kim and Adetimirin, 1997; Annor and Badu-Apraku, 2016). Therefore, combined nitrogen use efficiency and resilience to drought must be considered when developing maize genotypes for cultivation in SSA.

Normal endosperm maize grain contains ∼10% protein. However, the levels of lysine and tryptophan are inadequate. This makes children fed on non-quality protein maize (non-QPM) without other dietary protein sources suffer growth deformities such as kwashiorkor due to malnutrition (Olakojo et al., 2007; Upadhyay et al., 2009; Mbuya et al., 2011; Annor et al., 2019; Bhadmus et al., 2021). Quality protein maize, however, can provide 73% of the protein needs of human beings and contains nearly twice the quantity of tryptophan and lysine in the non-QPM endosperm (Annor et al., 2019; Bhadmus et al., 2021). Conversely, the normal endosperm maize grain can supply only ∼46% of the human protein requirements and has a protein content of ∼1.81% lysine and 0.35% tryptophan (Krivanek et al., 2007; Obeng-Bio et al., 2019). Studies aimed at enhancing the creation of stress (combined drought and low N)-resilient extra-early white QPM inbred lines that reach physiological maturity between 80 and 85 days after planting (Oluwaranti et al., 2008; Badu-Apraku et al., 2012a,b) are therefore crucial in reducing nutritional and food insecurity among the rural, peri-urban, and urban populations in SSA. According to Badu-Apraku and Oyekunle (2012), extra-early maize genotypes mature before the onset of the dry season and are capable of escaping tropical drought. Extra-early maturing white QPM genotypes that contain alleles for resilience to low soil N and drought can survive the drought at the flowering and grain-filling periods during the growing seasons. The drought and low-N resilient maize can overcome the effects of climate change in the tropics, resulting in the reduction of the unpredictability of maize grain yields in SSA, particularly in the savannah zones, and the relatively shorter second growing season in the forest agro-ecological zones of the tropics (Badu-Apraku et al., 2013).

Because of the significance of QPM, numerous extra-early white QPM inbreds have been developed by scientists of the International Institute of Tropical Agriculture Maize Improvement Program (IITA-MIP). The major thrust of the maize improvement program has been to develop drought-resilient and high-yielding QPM synthetic cultivars and hybrids that are resilient to the prevailing stresses for the release and commercialization in SSA. However, this objective cannot be promptly achieved without adequate knowledge and a clear understanding of the responses of inbred lines developed in the program to stress conditions, especially low soil N and drought. According to Betrán et al. (2003) and Meseka et al. (2011), hybrid maize potential is largely linked with the performance of the parents, and hybrids or varieties that have one or two stress-resilient parents usually produce higher yields compared to those with both parents susceptible. Information on the responses of the parental inbreds under the prevailing stress conditions would enhance the development of efficient breeding strategies for generating maize genotypes for stress environments in SSA (Meseka et al., 2006). Hence, the reaction of inbred lines to stresses should be considered by breeders when developing stress-resilient hybrids aimed at overcoming the effects of climatic change in the tropics. However, data on the reaction of the existing extra-early maturing white QPM inbred lines to combined low soil N and drought is insufficient. The present study sought to (i) identify climate-smart QPM inbred lines that can tolerate drought and low N stresses and (ii) determine the association between grain yield and other agronomically desirable characters of 96 extra-early maturing white QPM inbred lines and four inbred checks under drought and low-N conditions.

2 Materials and methods

2.1 Experimental materials

The ninety-six (96) QPM inbreds used in the present study were developed from a cross between Pool 15 SR (a QPM donor source) and two extra-early *Striga*-resistant (SR) white normal endosperm inbreds by scientists of the IITA-MIP in Nigeria. Backcrossing the single cross hybrids (F_1 hybrids) to the normal endosperm parents resulted in the first backcross (BC_1) and second backcross (BC_2) filial generations. Subsequently, the BC_2 individuals were repeatedly self-pollinated to obtain 245 extra-early white QPM S_6 inbred lines. Based on the assessment of the opaqueness of the maize kernels under a light box and the results of the field evaluations under drought at locations in Nigeria, 96 QPM inbred lines (Table 1) were selected for the present study.

2.2 Field experiments

The 96 extra-early white QPM parental inbreds and four low N and drought-resilient normal endosperm maize checks (Table 1) were assessed in low soil nitrogen and moisture stress conditions in Nigeria. The experiment was conducted in drought environments at Bagauda, which is drought-prone lying at longitude 8°22′E, latitude 12°00′N, with an elevation of 580 m and an annual rainfall of 800 mm, during the 2012 rainy season (July–October).[1] It was

1 Although the data were collected about a decade ago, this study is still very relevant because there are no high-yielding extra-early white QPM hybrids combining drought and low-N resilience currently released and commercialized in the sub-region. It is therefore important to make any information that could aid the development and identification of outstanding extra-early QPM varieties available to all relevant stakeholders across the globe.

TABLE 1 List of 96 S_6 extra-early maturing white quality protein maize inbred lines and four checks used in the study.

S/N	Inbred	S/N	Inbred	S/N	Inbred
1	TZEEQI 1	36	TZEEQI 66	71	TZEEQI 153
2	TZEEQI 3	37	TZEEQI 67	72	TZEEQI 156
3	TZEEQI 6	38	TZEEQI 69	73	TZEEQI 157
4	TZEEQI 7	39	TZEEQI 71	74	TZEEQI 162
5	TZEEQI 8	40	TZEEQI 72	75	TZEEQI 164
6	TZEEQI 9	41	TZEEQI 73	76	TZEEQI 169
7	TZEEQI 11	42	TZEEQI 75	77	TZEEQI 175
8	TZEEQI 12	43	TZEEQI 78	78	TZEEQI 176
9	TZEEQI 13	44	TZEEQI 80	79	TZEEQI 178
10	TZEEQI 17	45	TZEEQI 87	80	TZEEQI 179
11	TZEEQI 20	46	TZEEQI 94	81	TZEEQI 181
12	TZEEQI 21	47	TZEEQI 95	82	TZEEQI 183
13	TZEEQI 27	48	TZEEQI 96	83	TZEEQI 184
14	TZEEQI 28	49	TZEEQI 99	84	TZEEQI 187
15	TZEEQI 29	50	TZEEQI 100	85	TZEEQI 190
16	TZEEQI 33	51	TZEEQI 101	86	TZEEQI 191
17	TZEEQI 34	52	TZEEQI 102	87	TZEEQI 196
18	TZEEQI 35	53	TZEEQI 105	88	TZEEQI 198
19	TZEEQI 36	54	TZEEQI 109	89	TZEEQI 206
20	TZEEQI 38	55	TZEEQI 111	90	TZEEQI 212
21	TZEEQI 39	56	TZEEQI 115	91	TZEEQI 213
22	TZEEQI 40	57	TZEEQI 123	92	TZEEQI 215
23	TZEEQI 41	58	TZEEQI 127	93	TZEEQI 223
24	TZEEQI 43	59	TZEEQI 132	94	TZEEQI 228
25	TZEEQI 44	60	TZEEQI 133	95	TZEEQI 230
26	TZEEQI 45	61	TZEEQI 134	96	TZEEQI 239
27	TZEEQI 49	62	TZEEQI 136	97	Check-TZEEI 13
28	TZEEQI 52	63	TZEEQI 137	98	Check-TZEEI 21
29	TZEEQI 57	64	TZEEQI 138	99	Check-TZEEI 39
30	TZEEQI 59	65	TZEEQI 139	100	Check-TZEEI 49
31	TZEEQI 60	66	TZEEQI 140		
32	TZEEQI 61	67	TZEEQI 142		
33	TZEEQI 62	68	TZEEQI 144		
34	TZEEQI 63	69	TZEEQI 145		
35	TZEEQI 64	70	TZEEQI 152		

also conducted under imposed drought stress during the dry season (November–March) of 2012/2013 at the IITA drought research field at Ikenne. Furthermore, the trial was established under low soil nitrogen and optimal nitrogen environments at Mokwa and low soil nitrogen at Ile-Ife during the 2012 rainy season. A 10 ×10 simple lattice design with two (2) replications was utilized for all the experiments at the various sites. The experiments were made up of one-row plots, 4-m long with 0.75-m inter-row spacing and 0.40-m within-row spacing. Three seeds were sown per hole at planting and thinned to two 14 days after planting (DAP) to achieve ∼66,000 plants ha^{-1} population density. The experimental site at Ikenne has ∼1,200 mm of annual rainfall and is found in Nigeria at longitude 6°87′N, latitude 3°7′E, and 30 meters elevation. On the other hand, Mokwa is situated at longitude 5°4′E, latitude 9°18′N, 457 m altitude, and has an average annual rainfall of 1,100 mm, whereas Ile-Ife records an average annual rainfall of 1,200 mm and is positioned at a longitude 4°33′ E, latitude 7°28′ N, and 244 m above sea level in Nigeria.

At Ikenne, drought stress was imposed by stopping the irrigation water application 21 DAP to ensure the drought occurred at the bloom and grain-producing stages. Throughout the first 21 days of crop growth and development, a sprinkler irrigation system was utilized to make available 17 mm of water each week, as demonstrated in a similar research conducted by Annor and Badu-Apraku (2016) and Annor et al. (2019). The Ikenne experimental site is characterized as eutric nitisol soils with a high water-holding capacity. At planting, the drought experiments were fertilized by applying 60 kg ha^{-1} of phosphorus (P), 60 kg ha^{-1} of nitrogen (N), and 60 kg ha^{-1} of potassium (K). Additionally, 60 kg ha^{-1} of nitrogen was applied at 14 DAP. To ensure that the trials were weed-free, gramoxone and atrazine were applied as post- and pre-emergence weedicides at 5 l/ha of paraquat and primextra. The weedicides application was supplemented by manual weeding.

The selected maize inbreds were also assessed at the Mokwa and Ile-Ife experimental sites, which had been continuously depleted of nitrogen for several years by removing the biomass of cultivated maize after each harvesting. To ascertain the amount of nitrogen in the soil, samples of soil were taken from 0 to 15 cm depth for analysis at the soil laboratory of IITA in Ibadan, Nigeria, before planting (after land preparation). The soil analysis was done following the Association of Official Analytical Chemists (AOAC, 1984) procedure. Based on the nitrogen level in the soil (soil analysis results), urea fertilizer was applied to bring the nitrogen content of the low soil nitrogen plots to about 30 kg ha^{-1}, while the level of the optimal nitrogen block was increased to 90 kg ha^{-1} at 14 DAP. This brought the N, P, and K fertilizers applied to the low N conditions to 30, 60, and 60 kg ha^{-1}, respectively, while the N, P, and K fertilizers applied to the optimum N conditions were 90, 60, and 60 kg ha^{-1}, respectively.

Muriates of potash and single superphosphate were applied to the low soil N and optimal N fields to achieve 60 kg ha^{-1} of K_2O and 60 kg ha^{-1} of P_2O_5. To reduce the nitrogen fertilizer movement from one block to the other, the low and optimal nitrogen experiments were carried out in adjacent blocks set apart by a 10-m alley. The other agronomic practices carried out were as reported earlier for the drought trials.

2.3 Data collection

Data were taken on: days to 50% silking (DS) = the number of days between planting and when 50% of the plants' silks appeared; days to 50% anthesis (DA) = the number of days from planting and when 50% of the plants began to shed pollen grains. The anthesis-silking interval (ASI) was estimated as the difference between DA and DS; plant height (cm) = the distance between the plant's base and the height of the first tassel branch (for 10 randomly selected plants); ear height (cm) = the distance between the plant's base and the height of the node carrying the upper ear (mean of 10 randomly selected plants); root lodging was taken as the percentage of plants that leaned more than 30 degrees from the vertical; stalk lodging = the proportion of plants that had broken at or below the highest ear node; husk cover = measurement of how tight or loose the ear tip was (rating was on a scale of 1 to 9, with 1 indicating husks densely packed and extending beyond the ear tip and 9 indicating ear tips exposed); ear aspect = the overall look of the ears without the husks (ear aspect was graded on a scale of 1–9 based on ear size, uniformity of size, color, and texture, level of grain filling, and insect and disease damage); ears per plant (EPP) = the number of ears collected per plot divided by the number of plants in a plot at harvest; plant aspect was scored on a scale of 1 to 9 (Amegbor et al., 2017) based on the assessment of overall design of plants in a plot as they appealed to sight; and stay-green characteristic was rated at 70 DAP (10 WAP) on a scale of 1–9 (Annor and Badu-Apraku, 2016) based on the percentage of dead leaves in the low N and drought trials. Harvested ears from each plot were shelled, and grain weight was assessed in tests conducted under low N and drought conditions. The moisture content of the grains was tested using the Kett moisture tester PM-450. Grain yield in kg ha^{-1} was determined using shelled grain weight and a moisture level of 15%. However, for the optimal experiment, a shelling percentage of 80% for inbred lines per plot was assumed, and grain yield (obtained from ear weight converted to kg ha^{-1}) was adjusted to 15% moisture content.

2.4 Statistical analysis

The square root transformation method was used to transform the data recorded for stalk lodging, ear rot, and root lodging after converting them to percentages. The Statistical Analysis System (SAS) (SAS Institute, 2011) was used for the analysis of variance (ANOVA) of the data taken across the stresses (low N and drought) and under optimal conditions. The entries (inbreds) were considered fixed factors, while the environments, incomplete blocks within replicates × environment interactions, and replicates within the environments were considered random factors in the ANOVA across the stress conditions. The means that were estimated with SAS were separated by the standard error (S.E).

To identify stress-resilient inbred lines for the present study, a base index (BI), which comprised grain yield, plant aspect (PASP), ears per plant (EPP), anthesis-silking interval (ASI), stay-green characteristic (STGR), and ear aspect (EASP), was used as reported by Annor and Badu-Apraku (2016). The stress BI was estimated as follows:

$$BI = [(2\ x\ grain\ yield) + EPP - -PASP - -ASI - -STGR - -EASP]$$

To minimize the effects of the different scales, a mean of zero and a standard deviation of BI were used to standardize the traits. A negative BI estimate was an indicator of the susceptibility of an inbred, while a positive estimate was a sign of an inbred's resilience to stress, as reported by other researchers (Annor and Badu-Apraku, 2016).

The SAS PROC Varcomp was used to compute the heritability in the broad sense (H^2) for the observed variables under stress conditions by estimating the phenotypic and genetic variation of the inbreds. The heritability values were obtained using the formula below:

$$H^2 = \frac{\sigma_g^2}{\sigma_g^2 + \frac{\sigma_{ge}^2}{e} + \frac{\sigma_e^2}{re}}$$

where σ_{ge}^2 is the genotype x environment interaction, σ_g^2 is the genotypic variance, σ_e^2 is the error variance, r is the number of replicates per environment, and e is the number of environments (Fehr, 1991).

The association between the measured traits was determined by estimating the correlation coefficients using the PROC CORR in SAS. Employing the grain yield data for the inbreds, the genotype main effects plus genotype x environment interaction (GGE) biplot analysis was performed to break down the inbred x environment interactions into their components and to obtain the information on the most promising inbreds across the research conditions as described by Yan (2001).

3 Results

3.1 Variance analysis of grain yield and other agronomic parameters of 96 extra-early white quality protein maize inbred lines and checks

The combined ANOVA over four stress environments of the inbred lines revealed differences ($P < 0.01$) among inbreds and environments for measured parameters in the study. Under optimum conditions, there was genotypic variation for all parameters except for ear and plant heights. The ANOVA also revealed that inbred x environment interaction was highly variable for measured parameters apart from the number of ears per plant (Table 2).

3.2 Performance of inbred lines under stress and optimum conditions

Under stress conditions, the mean grain production of the inbreds varied from 447 kg ha^{-1} for TZEEQI 223–1,567 kg ha^{-1} for TZEEQI 60, with an overall mean of 1,020 kg ha^{-1}. Under optimum conditions, grain yield ranged from 744 kg ha^{-1} for TZEEQI 239–2,582 kg ha^{-1} for TZEEQI 7, with a mean of 1,838 kg ha^{-1}. Among the best 15 and worst 10 of the 96 extra-early QPM inbred lines selected based on their performance under stress conditions using the IITA base index, viz. inbreds TZEEQI 60, TZEEQI 7, TZEEQI 111, TZEEQI 78, and TZEEQI 137 with mean grain yield of 1,560, 1,404, 1,529, 15,667, 1,494, and 1,382 kg ha^{-1}, respectively, proved to be superior in terms of grain yield and resilience to drought and low nitrogen stresses in comparison with the four normal endosperm drought and low nitrogen-resilient normal maize checks (TZEEI 13, TZEEI 21, TZEEI 39, and TZEEI 49) (Table 3). The yield of these QPM inbred lines except TZEEQI 137 was also significantly higher than those of the most stress-resilient normal endosperm inbred check, TZEEI 21 (based on the

TABLE 2 Grain yield and other agronomic parameters of 96 extra-early white QPM maize inbreds and four checks assessed under low soil nitrogen, drought stress, and optimal growing conditions in Nigeria, 2012.

Source	df	Grain yield (kg ha^{-1})	Days to 50 % silking (days)	ASI (days)	Plant height (cm)	Ear height (cm)	Plant aspect (1−5)a	Ear aspect (1−5)b	Ear plant-1 (no.)	Leaf death (1−9)c
Stress environments										
Environment (Env.)	3	76,680,679**	936.76**	245.86**	246,936**	65,881.00**	30.51**	22.43**	8.86**	74.48**
Rep (Env)	4	1,260,865	19.47	9.12**	315.27**	731.65*	1.16	0.74**	0.24	1.27
Block (Env*Rep)	72	351,072**	8.82**	4.10**	387.94**	178.59**	0.40**	0.26**	0.11	0.62**
Entry	99	792,112**	41.05**	7.04**	659.35**	355.29**	0.35**	0.45**	0.15**	1.05**
Entry*Env	297	319,572**	6.45**	3.34**	195.01**	103.64**	0.19**	0.20**	0.09	0.54**
Error	324	144,786	3.75	2.57	136.74	63.53	0.13	0.12	0.09	0.3.0
Optimal environments										
Rep	1	696,255	0.02	0.32	206.05	0.61	0.001	0.15	0.11	
Block (Rep)	18	494,726**	4.44**	2.56	331.20	105.77	0.24	0.26	0.05	
Entry	99	903,140**	23.19**	5.60**	256.67	90.92	0.31**	0.30**	0.04*	
Error	81	189,781	1.66	2.13	360.05	107.48	0.12*	0.11**	0.03	

*, ** significant at 0.05 and 0.01 probability levels, respectively; Env., environment; Rep, replication; ASI, Anthesis-silking interval.

TABLE 3 Grain yield and other agronomic traits of etra-early white quality protein maize inbred lines (the best 15 and the worst 10 based on base index) and four normal checks evaluated under low -N, drought stress, and optimum conditions in Nigeria, 2012.

Inbred	Grain yield		Days to 50% silking		ASI		Plant aspect		Ear aspect		Ears plant^{-1}		LD	% YRD	Base Index
	ST	OPT	ST	OPT	ST	OPT	ST	OPT	ST	OPT	ST	OPT	ST	ST	
	kg ha^{-1}				Days										
TZEEQI 7	1,559.5	2,581.9	58.5	55.2	1.0	0.7	3.1	2.2	2.7	2.1	0.8	1.0	3.3	39.6	10.8
TZEEQI 78	1,404.3	2,101.2	59.2	56.3	0.2	0.1	3.3	2.5	3.0	2.7	0.8	0.9	3.3	33.2	8.6
TZEEQI 111	1,529.0	2,082.5	59.2	56.3	2.1	0.2	3.1	2.6	3.0	3.2	0.9	0.9	3.3	26.6	8.5
TZEEQI 60	1,566.9	2,111.8	59.7	61.5	1.5	3.7	3.1	2.7	3.0	2.8	0.7	0.9	3.3	25.8	8.2
TZEEQI 61	1,493.7	2,265.9	56.9	56.3	1.4	0.9	3.1	3.0	3.0	2.3	0.8	1.1	3.6	34.1	7.3
TZEEQI 137	1,381.9	2,251.1	57.8	54.1	1.7	0.5	3.1	3.0	2.8	2.6	0.8	0.9	3.7	38.6	6.9
Check-TZEEI 21	1,122.4	2,362.2	56.9	56.2	1.1	0.7	3.1	2.1	3.1	2.5	0.7	1.3	2.5	52.5	6.8
TZEEQI 66	1,426.5	2,185.3	61.0	55.1	3.1	1.3	2.9	2.8	2.9	2.5	0.6	1.1	3.3	34.7	6.6
Check-TZEEI 49	1,328.6	2,010.1	50.6	52.8	0.8	1.1	3.2	3.0	3.0	2.8	0.8	1.0	3.7	33.9	6.5
TZEEQI 139	1,398.2	2,285.2	56.9	53.9	2.3	1.4	3.1	2.3	2.9	2.5	0.7	0.9	3.5	38.8	6.3
TZEEQI 6	1,387.8	1,975.6	55.5	54.9	1.3	0.5	3.3	3.8	2.8	2.9	0.7	1.0	3.6	29.7	6.3
TZEEQI 8	1,492.6	2,290.0	57.7	56.1	2.2	1.9	3.2	2.7	2.9	2.0	0.6	0.7	3.6	34.8	6.2
TZEEQI 12	1,388.6	2,216.4	58.4	55.4	2.4	1.2	3.1	2.2	2.9	2.4	0.7	1.0	3.6	37.3	5.8
TZEEQI 63	1,379.5	2,235.3	59.4	56.7	1.0	1.6	3.1	2.3	3.3	2.4	0.6	1.1	3.5	38.3	5.6
TZEEQI 33	1,508.3	2,292.5	60.0	56.6	0.4	2.7	3.4	2.7	3.1	2.3	0.7	1.0	3.8	34.2	5.6
TZEEQI 72	1,148.5	1,739.7	56.2	54.2	0.7	0.1	3.4	2.8	2.9	3.1	0.8	1.1	3.4	34.0	5.5
TZEEQI 11	1,279.0	2,348.9	57.0	55.4	2.2	1.2	3.2	2.8	3.0	2.4	0.7	1.1	3.3	45.6	5.2
Check-TZEEI 39	1,218.0	1,698.9	57.5	56.9	2.1	1.1	3.5	3.0	2.7	2.7	0.8	0.8	3.5	28.3	4.9
Check-TZEEI 13	1,243.8	2,019.7	58.2	56.4	1.8	0.8	3.4	2.5	3.0	2.7	0.8	1.1	3.9	38.4	3.5
TZEEQI 132	638.3	1,212.3	61.1	55.0	3.9	1.3	3.7	3.4	3.4	3.4	0.4	0.7	4.0	47.3	−8.8
TZEEQI 230	526.5	1,317.9	62.1	66.6	2.9	4.3	3.6	3.2	3.5	3.6	0.5	0.4	4.4	60.1	−9.1
TZEEQI 179	497.8	1,182.7	61.4	64.4	3.2	5.1	3.8	3.5	3.7	3.3	0.5	1.2	3.9	57.9	−10.2
TZEEQI 206	572.7	1,847.6	61.9	64.0	3.8	2.3	3.6	3.1	3.8	3.3	0.6	0.8	4.4	69.0	−10.5
TZEEQI 184	547.0	1,006.9	63.1	63.0	3.1	4.3	3.7	3.9	3.5	3.7	0.5	1.1	4.6	45.7	−10.5
TZEEQI 239	537.6	743.7	64.5	68.0	4.6	7.1	3.6	3.1	3.6	3.8	0.4	0.4	4.3	27.7	−11.0

(Continued)

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TABLE 3 (Continued)

Inbred	Grain yield		Days to 50% silking		ASI		Plant aspect		Ear aspect		Ears plant^{-1}		LD	% YRD	Base Index
	ST	OPT	ST	OPT	ST	OPT	ST	OPT	ST	OPT	ST	OPT	ST	ST	
	kg ha^{-1}				Days										
TZEEQI 187	469.1	1,910.5	65.5	62.0	4.4	3.2	3.7	3.0	3.4	3.0	0.3	0.8	4.2	75.4	−11.3
TZEEQI 213	458.5	955.0	62.4	65.6	3.8	7.3	3.5	3.1	3.9	3.6	0.3	0.6	4.2	52.0	−11.8
TZEEQI 212	476.3	1,053.8	64.3	63.5	3.5	1.9	3.8	3.5	3.9	3.6	0.4	0.7	4.2	54.8	−12.7
TZEEQI 223	447.0	1,012.9	66.2	67.8	5.6	5.8	3.9	3.3	4.0	3.1	0.4	0.6	4.3	55.9	−16.1
MEAN	1,019.8	1,838.4	59.3	57.6	2.2	1.7	3.4	3	3.2	2.9	0.7	0.9	3.8	44.4	
LSD (0.05)	345.4	601.6	1.9	2.6	1.6	2.9	0.4	0.7	0.4	0.7	0.3	0.3	0.5		

ST, Stress condition; OPT, Optimum condition; % YRD, Percentage yield reduction; ASI, anthesis–silking interval; LD, Stay green characteristic.

base index), with a mean grain yield of 1122 kg ha^{-1}. However, the grain yield produced by the QPM inbreds was not significantly different from that of TZEEI 49, which recorded the highest yield among the checks. The grain yield produced by the QPM inbreds TZEEQI 78, TZEEQI 7, TZEEQI 60, and TZEEQI 111 were also significantly higher than those of TZEEI 13 and TZEEI 39. Under optimum conditions, the QPM inbred line, TZEEQI 7, produced much more grain (2,582 kg ha^{-1}) than all the checks except TZEEI 21 (2,362 kg ha^{-1}). An average yield decrease of 44% was revealed for the inbred lines across drought and low nitrogen stresses. The grain yield reduction was accompanied by fewer ears per plant, a rise in ASI, days to silking, and poor ear and plant aspects (Table 3).

TABLE 4 List of 53 S_6 extra-early maturing white quality protein maize inbred lines and four checks identified in the present study.

Inbred	Base index	Inbred	Base index
TZEEQI 7	10.8	Check-TZEEI 13	3.5
TZEEQI 78	8.6	TZEEQI 95	3.5
TZEEQI 111	8.5	TZEEQI 1	3.0
TZEEQI 60	8.2	TZEEQI 43	2.9
TZEEQI 61	7.3	TZEEQI 40	2.8
TZEEQI 137	6.9	TZEEQI 69	2.7
Check-TZEEI 21	6.8	TZEEQI 228	2.5
TZEEQI 66	6.6	TZEEQI 99	2.4
Check-TZEEI 49	6.5	TZEEQI 57	1.9
TZEEQI 139	6.3	TZEEQI 28	1.8
TZEEQI 6	6.3	TZEEQI 21	1.7
TZEEQI 8	6.2	TZEEQI 36	1.7
TZEEQI 12	5.8	TZEEQI 181	1.7
TZEEQI 63	5.6	TZEEQI 41	1.6
TZEEQI 33	5.6	TZEEQI 153	1.6
TZEEQI 72	5.5	TZEEQI 73	1.6
TZEEQI 11	5.2	TZEEQI 183	1.6
TZEEQI 100	5.1	TZEEQI 67	1.5
TZEEQI 64	5.0	TZEEQI 134	1.4
Check-TZEEI 39	4.9	TZEEQI 39	0.8
TZEEQI 49	4.6	TZEEQI 35	0.6
TZEEQI 136	4.6	TZEEQI 178	0.6
TZEEQI 45	4.3	TZEEQI 138	0.5
TZEEQI 44	4.3	TZEEQI 13	0.3
TZEEQI 80	4.3	TZEEQI 175	0.2
TZEEQI 133	4.2	TZEEQI 102	0.2
TZEEQI 157	4.0	TZEEQI 109	0.1
TZEEQI 20	3.8		
TZEEQI 71	3.7		
TZEEQI 27	3.7		

Based on the base index, 57 out of the 96 QPM inbred lines assessed across low nitrogen and drought stresses showed variable degrees of stress resilience (Table 4).

3.3 Relationship among the measured characters across stress environments

In the current study, grain yield had a high positive association with EPP but significant and negative relationships with days to 50% anthesis, ASI, days to 50% silking, ear height, plant aspect, ear aspect, and leaf death scores across the two (2) stress environments (Table 5). Heritability estimates for the measured traits varied from 0.00 for husk cover to 0.85 for days to 50% silking. The results revealed low heritability for root lodging (0.14), husk cover (0.00), and stalk lodging (0.26). Moderately high heritability estimates were observed for plant aspect (0.46), anthesis-silking interval (0.50), ear aspect (0.56), number of ears per plant (0.39), leaf death (0.47), and ear rot (0.42), while grain yield (0.65), days to 50% silking (0.85), days to 50% anthesis (0.84), ear height (0.73), and plant height (0.72) recorded very high heritability estimates across the two stress conditions (Table 5).

3.4 Grain yield performance and stability of selected QPM inbred lines across stress and optimum growing conditions

The significant genotype x environment interactions and genotypes for most measured traits across stress and optimum conditions justified using the GGE biplot to examine the yield performance and stability of the QPM inbreds across test environments. The GGE biplot is based on the grain yield performance of the 25 (20 best and five worst) QPM inbreds and four normal endosperm inbred checks studied across the stress and optimal conditions. The stability of inbred lines is determined by their projections onto the ATC abscissa. Thus, the longer the projection of an inbred line onto the ATC, the less the stability of the line. Based on these criteria, TZEEQI 7 (Entry 1) was the most stable and highest yielding, followed by inbred lines TZEEQI 60 (Entry 2) and TZEEQI 12 (Entry 10). Contrarily, TZEEI 63 (Entry 11) and TZEEQI 6 (Entry 13) were the least stable and lowest across test environments (Figure 1).

4 Discussion

To reduce malnutrition and improve food security in SSA, there is a pressing need for drought-resilient QPM inbreds with high nitrogen utilization efficiency (resilient to low N) and genes for drought resilience. Such inbred lines could be utilized to develop high grain-producing QPM hybrids and synthetic cultivars resilient to both stresses. The differences detected among the inbreds, inbred x environment interactions (GEI), and environments observed in this study for most measured traits under stress and optimum conditions suggested that the test environments varied enough to enable the selection of inbred lines with outstanding performance, as indicated by Badu-Apraku et al. (2011, 2016). The results also suggested that adequate genetic variation existed among the genotypes to allow them to be utilized as sources of beneficial alleles for the development of extra-early white QPM breeding populations for resilience to low soil N and drought conditions. The current result agrees with the reports of Badu-Apraku and Oyekunle (2012) and Adu *et al.* (2021). Moreover, the varied GEI and environments revealed for most of the measured parameters of the inbreds across stress conditions indicated that there could be differences in the expression of the traits under the stress conditions. The implication is that the evaluations of the inbreds in more stressful environments would be required for the identification of the most outstanding inbred lines, as stated by other researchers under drought stress conditions (Badu-Apraku et al., 2011; Edmeades, 2013; Adu et al., 2021) and under low soil N (Meseka et al., 2006). This result endorses the substantial role that the growing environment plays in detecting genotypes with an outstanding performance across the two stress conditions.

The most important aim of the current study was to discover outstanding inbred lines for generating climate-smart synthetic cultivars and hybrids for SSA. Such outstanding inbred parents could also be used as sources of valuable alleles for stress resilience. Stress-resilient inbred lines would be priceless in maize breeding programs to develop stress-resilient and high grain-producing synthetic cultivars and hybrids (Betrán et al., 2003; Meseka et al., 2011) for cultivation in SSA. Fifty-seven (57) out of the 96 QPM inbred lines assessed under the stress conditions were found to be resilient to stress at different levels. The stress-resilient hybrids identified also had high grain yield, superior ear aspect, short ASI, high number of ears per plant, good stay-green characteristics, and better plant aspect. Therefore, the superior inbreds identified under stress situations would be valuable for the development of QPM populations in addition to the generation of high-yielding and stress-resilient synthetic cultivars and hybrids for commercialization in SSA. They will also be a good source of invaluable alleles for stress resilience.

The QPM inbreds TZEEQI 60 and TZEEQ1 7 were the best in terms of stability and yield across environments. The most stable and highest yielding QPM inbred, TZEEQI 7, out-yielded the best low nitrogen and drought-resilient normal endosperm check, TZEEI 21, by 28.0% under stress and 8.5% under optimum conditions. The low levels of yield reduction observed for the top-yielding inbred lines, compared to the checks, indicated the presence of genes for stress resilience in the inbred lines evaluated. The reduction in grain yield, along with an increase in ASI and days to silking, poor plant and ear aspects, and few ears per plant, suggested that the selection for reduced days to anthesis, shorter ASI, increased ears per plant, and good plant and ear aspects is the best method for breeding for stress resilience in the set of inbred lines used. The results in the current study concord with those by Badu-Apraku et al. (2011) and Adu et al. (2021), who suggested that the stay-green characteristic, plant aspect, ASI, and EPP should be considered for selecting genotypes in drought environments. Guei and Wassom (1992) and Badu-Apraku et al. (2023) also indicated that improvement in stress tolerance requires a good stay-green characteristic, shorter ASI, and an improved number of ears per plant. Short ASI, delayed leaf senescence, and an increased number

TABLE 5 Heritability estimates and Pearson's correlation coefficients for grain yield and other agronomic characters of 96 extra-early white quality protein maize inbred lines and four checks evaluated across drought and low N environments in Nigeria, 2012.

	YIELD	DA	DS	ASI	PLHT	EHT	RL	SL	HUSK	PASP	EASP	LD	EPP	EROT
POLLEN	−0.44**													
DASK	−0.61**	0.91**												
ASI	−0.61**	0.27**	0.65**											
PLHT	−0.10	0.25*	0.31**	0.24*										
EHT	−0.27*	0.42**	0.44**	0.24*	0.66**									
RL	0.05	−0.29**	−0.32**	−0.20*	−0.25*	−0.12								
SL	0.00	−0.33**	−0.31**	−0.12	−0.05	0.14	0.46**							
HUSK	−0.07	−0.03	−0.03	−0.02	−0.12	−0.25*	0.03	−0.14						
PASP	−0.63**	0.29**	0.36**	0.30**	−0.25*	−0.04	0.19	0.02	0.16					
EASP	−0.77**	0.45**	0.56**	0.47**	0.13	0.26**	−0.08	−0.08	0.11	0.66**				
LD	−0.51**	0.23*	0.33**	0.33**	0.09	0.37**	0.04	0.26**	−0.08	0.47**	0.46**			
EPP	0.56**	−0.44**	−0.51**	−0.36**	−0.17	−0.11	0.20*	0.17	−0.03	−0.43**	−0.56**	−0.19		
EROT	0.09	−0.03	−0.11	−0.18	−0.13	−0.14	0.01	−0.15	0.19	−0.09	0.04	−0.03	0.14	
Heritability	0.65	0.84	0.85	0.50	0.72	0.73	0.14	0.26	0.00	0.46	0.56	0.47	0.39	0.42

*, **significant at 0.05 and 0.01 probability levels, respectively; YIELD, grain yield; DA, days to 50% anthesis; DS, days to 50% silking; ASI, anthesis-silking interval; PLHT, plant height; EHT, ear height; SL, stalk lodging; RL, root lodging; HUSK, husk cover; PASP, plant aspect; EASP, ear aspect; LD, leaf death; EPP, number of ears per plant; EROT, ear rot.

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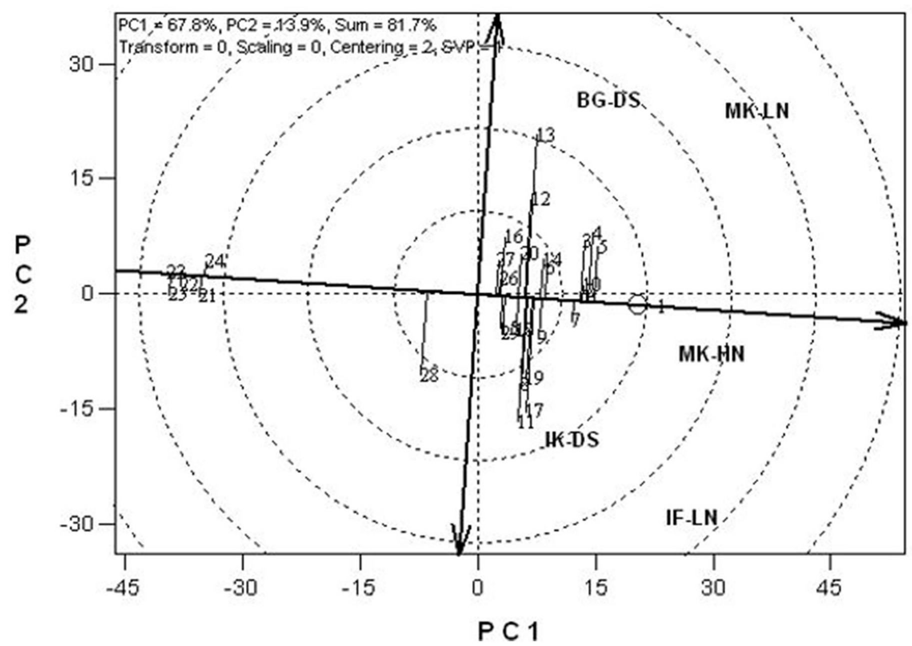

FIGURE 1
The yield performance and stability of 25 extra-early maturing white QPM inbred lines and four normal endosperm extra-early maize inbred checks evaluated under drought, low N, and optimum growing conditions at Bagauda, Ikenne, Ile-Ife, and Mokwa (1 = TZEEQI 7; 2 = TZEEQI 60; 3 = TZEEQI 33; 4 = TZEEQI 8; 5 = TZEEQI 6; 6 = TZEEQI 111; 7 = TZEEQI 66; 8 = TZEEQI 139; 9 = TZEEQI 137; 10= TZEEQI 12; 11 = TZEEQI 63; 12 = TZEEQI 78; 13 = TZEEQI 6; 14 = TZEEQI 11; 15 = TZEEQI 136; 16 = TZEEQI 73; 17 = TZEEQI 64; 18 = TZEEQI 134; 19 = TZEEQI 35; 20 = TZEEQI 133; 21 = TZEEQI 179; 22 = TZEEQI 212; 23 = TZEEQI 239; 24= TZEEQI 213; 25 = TZEEQI 223; 26 = Check-TZEEI 13; 27 = Check-TZEEI 21; 28 = Check-TZEEI 39; 29 = Check-TZEEI 49; IF-LN = Ile-Ife low nitrogen; MK-LN = Mokwa low nitrogen; MK-HN = Mokwa high nitrogen; BG-DS = Baguada drought stress; IK-DS = Ikenne drought stress).

of ears per plant in stress environments, according to Edmeades et al. (1993) and Zhao et al. (2022), are signs of better growth rates of ovules under stress and increased allocation of assimilates to the emerging ear. The grain yield losses of 44.4% for inbreds under stress conditions in the current study is within the range reported by workers in other studies (NeSmith and Ritchie, 1992; Menkir and Akintunde, 2001; Derera et al., 2008; Badu-Apraku et al., 2011).

The moderate to very high estimates of heritability ($\geq$0.30) recorded in the current study for the plant aspect, anthesis-silking interval, grain yield, days to 50% anthesis, ear aspect, number of ears per plant, leaf death, ear rot, days to 50% silking, ear, and plant heights in stress environments showed that the parameters might be easily transferred to the progenies and phenotypic selection would also be effective since additive gene action is more important than non-additive gene action for most of the measured traits. The results also suggested that early generation selection for the characters under stress could be effective, as reported in other studies by Bänziger et al. (1999), Badu-Apraku et al. (2013), and Annor and Badu-Apraku (2016). The results of the present study are at variance with those of Badu-Apraku et al. (2011), who evaluated a set of inbred lines in stress environments and reported that selection for grain yield directly would not be effective due to the low heritability recorded for the trait. The low heritability recorded for husk cover, stalk lodging, and root lodging under stress conditions implied that phenotypic selection of the traits might not be promising, and therefore, the use of selection indices or indirect selection method would be required to assess the genetic values of the traits as indicated by Mhike et al. (2011).

The relationship found between grain yield and EPP suggested that the indirect selection of an increased number of ears per plant could result in improved grain yield across the two stress environments. Musila et al. (2010) also reported a strong positive connection between grain yield and the number of ears per plant across stress conditions. Contrarily, a negative relationship was displayed between grain yield and ASI, days to 50% anthesis, ear height, days to 50 % silking, plant aspect, leaf death, and ear aspect, indicating that selection for reduced ASI, ear height, days to 50% anthesis, plant aspect, days to 50% silking, ear aspect, and leaf death could improve grain yield in stress environments. A reliable secondary character for selecting genotypes for stress tolerance must have a strong relationship with grain yield, be highly heritable, and be very simple to record (Bänziger et al., 2000; Adu et al., 2021). Hence, grain yield, ASI, ear height, days to 50% anthesis, plant aspect, days to 50% silking, ear aspect, EPP, and leaf death could be very useful for selecting stress-resilient genotypes among the QPM inbred lines utilized in the current study. This report supported the discoveries of Betrán et al. (2003), Badu-Apraku et al. (2011), Badu-Apraku and Oyekunle (2012), Adu et al. (2021) that the most dependable characters for the identification of high yielding maize inbreds in stress environments were plant aspect, ASI, EPP, leaf death, ear aspect, and grain yield. Inbred lines TZEEQI 7, TZEEQI 12, and TZEEQI 60 were found to have exceptional stability and yield across the research environments and could be employed to produce outstanding QPM synthetics and hybrids for commercialization in SSA.

5 Conclusion

The inbred lines exhibited differences in the ability to tolerate low N and drought, with an average grain yield reduction of 44.4%. Moderate to high estimates of heritability were displayed by the majority of the studied characters across low N and drought, indicating that several measured characters studied could be easily transferred from the parental inbreds to the progenies and that selection could be done directly. Fifty-seven QPM inbred lines were found to be stress-resilient and could be easily employed as genetic resources for the incorporation of low N and drought-resilient genes into QPM populations in the tropics and the development of stress-resilient synthetic and hybrid cultivars in SSA.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: the datasets used in the present study have been deposited at the IITA CKAN repository http://data.iita.org.

Author contributions

BA and BB-A were involved in the experimental design, data collection, analysis, interpretation, and the entire write-up.

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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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Strategic Foresight analysis of droughts in southern Africa and implications for food security

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Southern Africa has been experiencing long-term changes in its climate and future projections imply that droughts should last longer and become more intense in southern Africa. Already, the region has been experiencing an increase in consecutive drought years. This study contributes to the literature by using bio-economic modeling to simulate the impact of future droughts on food security in southern Africa and identify plausible pathways for enhancing regional food security under drought. Food production and food security in southern Africa were projected under drought using an adjusted version of a multi-market and multi-commodity global model, the International Model for the Policy Analysis of Agricultural Commodities and Trade (IMPACT), version 3.2. The results suggest that with moderate economic growth and no drought, southern Africa would not become wealthy enough to mitigate food insecurity by 2040. In this context, recurrent droughts would worsen food security by severely affecting the production of maize, the key staple food in the region. With consecutive two-year regional droughts, like what was experienced in 2014/15 and 2015/16, most countries would experience an increase of at least 10% in the number of people at risk of hunger within a single year. Key measures which could help enhance food security under droughts include (1) breeding for stress-resilient maize (resistance to both heat and drought stresses); (2) promote crop and diet diversification, especially in countries highly dependent on maize as a staple food crop; and (3) invest in rainwater harvesting.

KEYWORDS

southern Africa, drought, bio-economic modeling, food security, strategic foresight

1 Introduction

Africa in general and Southern Africa in particular has been experiencing long-term changes in climate. More specifically, the observed mean surface air temperature has been increasing across Africa since 1980 and this is consistent with global warming trends (Hulme et al., 2001; Nicholson et al., 2013). In southern Africa, rising temperatures have also been observed (Sheffield and Wood, 2008; Jury, 2013). In addition, studies have shown that droughts are lasting longer and have also become more intense across the region whereas their frequency has increased in the northern part of the region (Fauchereau et al., 2003). In South Africa, the frequency of two-year consecutive drought has increased (Rouault and Richard, 2005).

Projections suggest that average precipitation would decrease in southern Africa, although heavy precipitation events are projected to increase. Consecutive dry days are also projected to increase across the region compared to today (Kitoh and Endo, 2016). In terms of weather extremes, an increase in the duration and intensity of droughts is projected for southern Africa (Seneviratne et al., 2012).

As a key staple food in the region, maize is a priority crop which receives considerable national attention. In Zambia, the bulk of the agricultural subsidies is directed toward maize (Culas and Hanjra, 2011). In Malawi, where the bulk of the maize is produced for own home consumption, the government operates a price band system to support maize production and control consumer prices (FAO, 2015). In Lesotho, Zimbabwe, Eswatini and Mozambique, maize also plays a central role in national food security policies (Mphale et al., 2003; Mudimu, 2003; Manyatsi and Mhazo, 2014; FAO, 2016).

However, maize is sensitive to soil moisture stress especially at flowering stage (Cairns et al., 2012). Jayanthi et al. (2014) used past weather data to estimate drought risk for maize production in the sub-regions of Malawi and Mozambique. The southern region of Malawi was found to be more prone to drought compared to the northern region. They made a similar conclusion for Mozambique where the southern region is expected to have drought return periods of 1 to 4 years which is lower than that of the northern region. Kamali et al. (2018) used biophysical and social indicators to assess drought vulnerability for maize in sub-Saharan Africa. They showed that southern Africa is more vulnerable to physical drought for maize. However, societal factors including national drought policy responses significantly influence maize vulnerability to drought across sub-Saharan Africa.

Given the future drought projections, it might be prudent to consider alternative crops as staple food in southern Africa. This foresight study contributes to the current literature by quantifying the bio-economic impact of future droughts in southern Africa; the results from this study should support disaster policies in southern Africa. The objectives of the study are:

- Simulation of the impact of future droughts on food security in southern Africa
- Identification of plausible pathways for enhancing regional food security under drought

The next section of the paper provides some background information on the importance of maize in the food diet and on the impact of past droughts on maize and agricultural production in southern Africa. The conceptual framework used in this study is described in section 3; results are presented in section 4 and they are followed by discussion in section 5. Section 6 concludes.

2 Background

This section analyzes current food consumption patterns in southern Africa to highlight the role of maize in the average diet. The section also describes the impact of past droughts on agricultural production in southern Africa. The crops considered in the analysis include maize, the key staple food crop, and major cash crops such as soybean, groundnut, cotton and tobacco. Cassava and cowpea which are drought-tolerant are also considered for contrast.

2.1 Key staple foods in southern Africa

Cereals provide 49% of the average *per capita* daily caloric intake in southern Africa followed by starchy roots; vegetable oils; meat, fish and eggs; and sugar & sweeteners (Figure 1). Across all countries in southern Africa, except Angola, cereals have the highest share among all food items, in terms of caloric intake. In Angola, starchy roots account for the highest share of daily caloric intake followed by cereals (Figure 1).

Cereal (wheat, maize, rice, oats, barley, rye, millet, and sorghum) consumption in southern Africa is 203 kg/person. However, maize accounts for 61% of cereal consumption. Compared to the world average, maize food consumption *per capita* in southern Africa is four times higher. It's only in Madagascar that rice dominates cereal consumption (Table 1).

The consumption of starchy roots as food in southern Africa stands at around 128 kg per person per year which is more than twice the world average. There are six countries in southern Africa where *per capita* food consumption of starchy roots is much higher than the world average; these countries also account for 58% of the total population in southern Africa. They include Angola, Malawi, Mozambique, Madagascar, Namibia, and Zambia. Across the region, cassava dominates consumption of starchy roots (Table 1).

Per capita consumption of vegetable oils in southern Africa is two-thirds that of the world average. It's only in South Africa that *per capita* consumption of vegetable oils is 1.11 times higher than that of the world average. In all other countries in southern Africa, except Angola, *per capita* consumption is half that of the world average or less. In addition, southern Africa is heavily dependent on imports to meet its vegetable oils requirements with approximately 64% of the consumed vegetable oils being imported. For some countries, namely, Zambia, Eswatini, Namibia and Botswana, imports account for 90% of total vegetable oil consumption. Palm oil tops vegetable oil consumption in southern Africa (Table 1).

Per capita consumption of meat, eggs & aquatic products in southern Africa is below that of the world average. The region is also a net importer, although it currently imports about 5% of its total consumption requirement. Poultry dominates regional meat consumption (Table 1).

Southern Africa is a net exporter of sugar and sweeteners: the region's exports amount to 17% of its total consumption (Table 1). *Per capita* consumption of sugar and sweeteners is close to that of the world average, although in Eswatini, consumption is 10 times higher than that of the world average. In Eswatini, most of the sugar consumed is allocated to other uses apart from food. For southern Africa, the consumption of sugar and sweeteners as food was 20 kg/capita/year on average between 2009 and 2011, which is slightly below than the world average, 24 kg/capita/year (Table 1).

2.2 Past drought effects in southern Africa

Between 2000 and 2016, all countries experienced incidences of drought: Botswana and Zimbabwe experienced the highest number of drought events with 5 and 7 years out of 16, respectively. On the other hand, with only 2 drought reports, Zambia and Angola experienced the least number of droughts (Table 2).

Drought reduces maize production by 3 to 67.7%, rice production by 3.5 to 62.4%, soybean production by 5.7 to 46.9%, groundnut production by 3.6 to 51.8%, and cotton production by 12.9 to 67.4% across countries in southern Africa (Table 3). In two countries, namely Zambia and Zimbabwe, cotton, tobacco and groundnut production decrease substantially due to drought. For maize, all countries except Angola

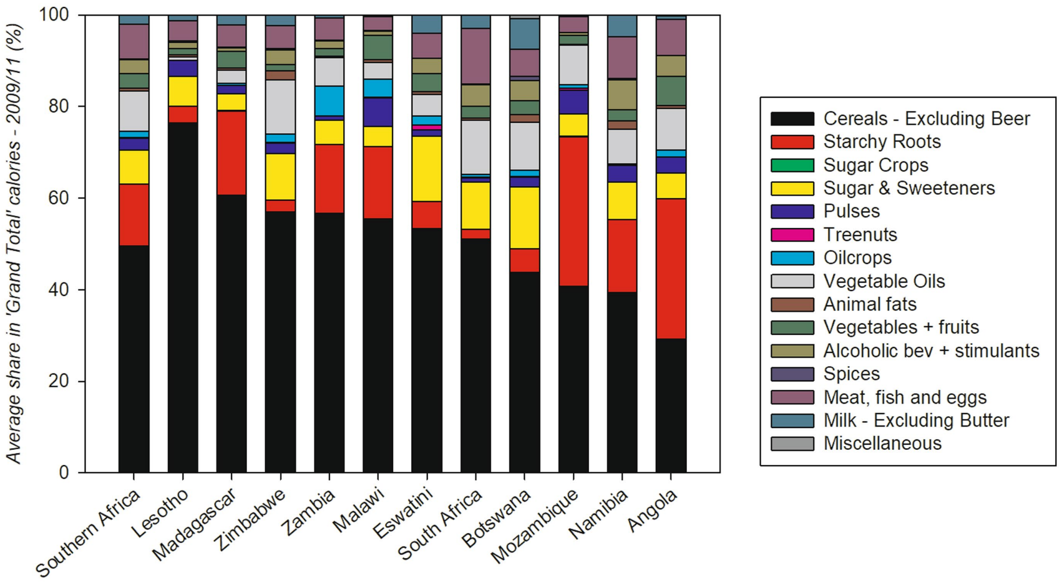

FIGURE 1
Contribution of staple food groups to daily caloric intake in southern Africa – average of 2009 to 2011). Source: authors' computations using data from FAOSTAT (2018).

experience a reduction in yields due to drought. In Mozambique, Namibia, South Africa, Eswatini, Zambia and Zimbabwe, reduced area under maize also occurs. Production changes due to drought are a result of effects on yield (kg/ha) and/or area (ha) and these effects vary across countries and crops. For example, in Madagascar, groundnut production increases by 1.5% under drought (Table 3). However, the yield effect from the drought is 1.1% whereas the area effect is about 0.40%.[1] On the other hand, groundnut production in Malawi increases by 18.8% under drought. However, the analysis of this change reveals that groundnut yield decreases by 9.9% under drought whereas acreage increases by 32%.[2] Malawian farmers are known to replace maize with groundnut when faced with drought (Okori, 2018).

Drought reduces available food supply and drives up food prices. In addition, drought erodes consumers' income, especially for smallholder farmers who experience a reduction in agricultural production and hence income. These farmers find it difficult to purchase imported food, which has become more expensive. Here, the two-year droughts of 2014/15 and 2015/16 cropping seasons are used to analyze the impact of drought on food prices in southern Africa. In 2016, after two years of consecutive droughts, total maize production across southern Africa was 34% lower compared to that for 2014, a year characterized by no drought in the region except in Madagascar (Table 3). Real food prices were substantially higher in 2016 compared to 2014 across the region except in Angola, Botswana, and Zimbabwe (Table 3). In Angola, nominal food prices were substantially higher in 2016 compared to that for 2014. However, the Consumer Price Index (CPI) decreased substantially between the two years such that real food prices did not change much. For Botswana and Zimbabwe, there were small changes in the nominal Food Price Index (FPI) and CPI; hence, real food prices did not change much in 2016 compared to 2014. These results are consistent with reports on food insecurity which imply that less than 3% of the population in Angola and Botswana was food insecure in 2016 after a two-year drought. Zimbabwe is a peculiar case where more than 25% of the population was food insecure in 2016, after two consecutive drought years but real food prices were smaller in 2016 compared to 2014. Here, it might be that droughts affected food security by primarily reducing incomes and hence food purchasing power (Table 3).

3 Materials and methods: bio-economic modeling approach

3.1 Projections on food production, consumption, and food security in southern Africa

Projections on food production and food security under drought scenarios in southern Africa were estimated using a process-based structural framework which combines crop, climate, hydrology, and economic models to globally project production, consumption, and food security under alternative scenarios of population and income growth (Islam et al., 2016).

The framework involves gridded crop modeling which is used to simulate pixel-level rainfed and irrigated crop yields under various climate change models (Figure 2). The simulated yields are inputted into an economic model, the International Model for the Policy Analysis of Agricultural Commodities and Trade (IMPACT), version 3.2 (Robinson et al., 2015). Within IMPACT, the simulated crop yields are adjusted over time by intrinsic productivity growth rates (IPRs) to reflect technological advancement in agriculture. IPRs are measured by combining expert knowledge with past trends in Total Factor Productivity (Robinson et al., 2013). Other inputs in IMPACT include exogenous trends on global

1 0.40=((1+1.5/100)/(1+1.1/100) − 1).
2 32=((1+18.8/100)/(1−9.9/100) − 1).

TABLE 1 Consumption of staple food items in southern Africa – average between 2009 and 2011.

Food	Variable	AGO	BOT	LSO	MDG	MWI	MOZ	NAM	S. Afr.	SWZ	ZMB	ZWE	Region	World
Cereals	Total consumption per person per year[1] (kg)	118	136	268	180	216	139	142	290	220	159	178	203	332
	Net Imports (% of total consumption)	59	88	78	11	−6	27	57	2	75	−26	53	13	
	Food consumption per person per year (kg)	85	111	232	130	149	110	100	178	136	128	155	141	147
	Main cereal	Maize	Maize	Maize	Rice	Maize	Maize	Maize	Maize	Maize	Maize	Maize	Maize	
	Share – main cereal in total consumption (%)	50	31	69	84	90	58	36	68	67	87	69	61	
	Maize food consumption per person per year (kg)	39	36	164	18	131	57	41	99	71	112	109	71	17
Starchy roots	Total consumption per person per year[1] (kg)	705	55	55	223	492	357	167	43	64	103	21	237	111
	Net Imports (% of total consumption)	0	16	9	0	0	0	6	5	15	0	3	1	
	Food consumption per person per year (kg)	267	49	50	155	194	249	137	32	56	97	20	128	62
	Main starchy root[2]	Cass	Other	Pot	Cass	Cass	Cass	Other	Pot	Other	Cass	Cass	Cass	
	Share – main starchy root in total consumption (%)	87	83	100	69	53	87	90	94	72	83	77	72	
Vegetable oil	Total consumption per person per year[1] (kg)	15	10	1	5	4	11	11	24	5	6	11	14	22
	Net Imports (% of total consumption)	72	95	50	83	53	52	100	59	94	92	76	64	
	Food consumption per person per year (kg)	9	10	1	2	3	8	6	15	4	5	11	9	11
	Main vegetable oil[3]	Palm	Sunfl.	Other	Palm	Gdnut	Palm	Sunfl.	Palm	Sunfl.	Palm	Soy.	Palm	
	Share – main oil in total consumption (%)	54	69	100	52	34	36	33	35	60	53	25	36	
Sugar & Sweetnrs	Total consumption per person per year[1] (kg)	18	42	17	8	11	11	17	34	279	10	26	22	28
	Net Imports (% of total consumption)	83	100	100	55	−102	−30	97	−21	−91	−169	−2	−17	
	Food consumption per person per year (kg)	15	31	17	8	11	11	17	34	32	10	24	20	24
Meat, fish & egg	Total consumption per person per year[1] (kg)	28	30	21	15	8	8	31	59	24	14	21	29	42
	Net Imports (% of total consumption)	61	−42	28	0	0	11	−14	9	14	1	9	13	
	Food consumption per person per year (kg)	28	29	21	15	8	8	33	58	23	14	20	29	42
	Main item[4]	Aqu.	Other	Bov.	Bov.	Aqu.	Aqu.	Aqu.	Poul.	Bov.	Aqu.	Bov.	Poul.	
	Share – main meat item in total consumption (%)	36	31	23	32	37	44	31	41	53	29	28	31	

Source: Authors' computations using data from FAOSTAT (2018).
AGO, Angola; BOT, Botswana; LSO, Lesotho; MDG, Madagascar; MWI, Malawi MOZ: Mozambique; NAM, Namibia; S. Afr., South Africa; SWZ, Eswatini; ZMB, Zambia; ZWE, Zimbabwe; Region, southern Africa.
1: total consumption per person per year: includes food, feed, seed, losses, processed, and other uses, etc. 2: Cass: cassava; Other: other roots & tuber; Pot: potato; 3: Palm: palm oil; sunfl: sunflower seed oil; other: other oil; Gdnut: groundnut oil; Soy: soybean oil; 4: Aqu.: Aquatic product; other: other meat; Bov: bovine meat; Poul: poultry meat.

TABLE 2 Past drought years (marked with "d") and corresponding maize production (000 MT) in 11 countries in southern Africa.

Year	Angola	Botswana	Lesotho	Madagascar	Malawi	Mozambique	Namibia	South Afr.	Eswatini	Zambia	Zimbabwe
1999	428.0	3.8	124.5	175.0[a]	2479.4[a]	1336.1	18.9	7946.0	124.1[a]	822.1	1519.6
2000	394.6	9.3	106.8[a]	169.8[dz]	2501.3 [a]	1180.4	31.6	11431.2	112.8[a]	1040.0	2108.1[a]
2001	428.8	5.0[d]	158.2[a]	179.6	1713.1	1143.3	27.7	7772.0[d]	82.5[dz]	802.0	1466.8[a]
2002	546.9	16.4	111.1[dz]	172.0	1557.0[dz]	1114.8	27.8	10076.0	67.6[dz]	606.2[dz]	605.0[dz]
2003	618.7	1.6[dz]	82.1[dz]	317.9	1983.4	1178.8	28.9	9705.0	69.3[dz]	1157.9	1059.0
2004	577.0	7.5[dz]	81.0[dz]	349.6	1608.3[dz]	1060.4[d]	28.2	9710.1	68.1[dz]	1214.0	1686.2
2005	734.4	16.1[a]	78.7	391.0	1225.2[dz]	942.0[d]	40.7	11715.9	74.5	866.2[dz]	915.4[dz]
2006	526.1	15.2[a]	100.8	405.3	2611.5	1417.8	60.9	6935.1[dz]	67.1	1424.4[a]	1484.8
2007	615.9	2.2[dz]	60.3[dz]	416.8	3226.4	1582.0	55.5	7125.0[dz]	26.2[d]	1366.2[a]	952.6[dz]
2008	702.4	9.0[dz]	59.7[dz]	430.3	2634.7	1676.0	58.1	12700.0[a]	60.0	1211.6	496.0[dz]
2009	970.2	20.1	57.1	425.2	3582.5	1612.0	57.3	12050.0[a]	57.0	1887.0	700.0[dz]
2010	1072.7[a]	10.6	128.2	411.9	3419.4	2089.9	65.0[a]	12815.0	84.7	2795.5	1192.4
2011	1262.2[a]	35.2	73.4	428.4	3699.1	2178.8[a]	53.8[a]	10360.0	75.4	3020.4	1452.0
2012	454.3[dz]	7.7[d]	16.8[d]	447.9	3618.7	1177.4[dz]	87.6[a]	11830.0	81.9	2852.7	968.0[dz]
2013	1548.8	3.8[d]	86.0	381.0	3639.9	1207.0	40.0[dz]	12486.0	118.9	2532.8	799.0[dz]
2014	1686.9	35.0	80.0	366.0[d]	3929.0	1357.2	68.0	14982.0	81.6	3350.7	1456.0
2015	1878.3	3.8[d]	70.8[d]	329.4[d]	2776.3[d]	1262.0[d]	60.1[d]	9955.0[d]	83.6[d]	2618.2	642.8[d]
2016	1500.0[d]	11.8[d]	25.0[d]	316.3[d]	2369.5[d]	1451.9[d]	63.7[d]	7778.5[d]	86.0[d]	2873.1	852.9[d]

Source: Angola: (FEWSNET, 2012c; Masih et al., 2014; FAO/GIEWS, 2016a); Botswana: (FEWSNET, 2007a; Central Statistical Office - Botswana, 2016; FAO/GIEWS, 2016f); Lesotho: (FEWSNET, 2004b, 2007a, 2012a; Masih et al., 2014; UN Office Lesotho, 2016); Madagascar: (FEWSNET, 2001b; Masih et al., 2014; USAID, 2016); Malawi: (FEWSNET, 2002a, 2004a, 2005a, 2015a, 2016a; Masih et al., 2014); Mozambique: (FEWSNET, 2004d, 2005b, 2012c, 2015b, 2016b; Masih et al., 2014); Namibia: (Kapolo, 2014; FAO/GIEWS, 2016b); South Africa: (FEWSNET, 2001a, 2006, 2007b; FAO/GIEWS, 2016c); Eswatini: (FEWSNET, 2001b, 2004e, 2004c, 2007c; FAO/GIEWS, 2016d; UN Office Eswatini, 2016); Zambia: (FEWSNET, 2002b, 2005c); Zimbabwe: (FEWSNET, 2002c, 2005d, 2007a, 2008, 2009, 2012b, 2013; FAO/GIEWS, 2016e).

Sources for production data is FAOSTAT (2018).

[d]: drought year; [a]: data used to estimate production during non-drought years; [z]: data used to estimate production under drought. For soybean in Malawi, non-drought years were 2006 and 2007 due to lack of data for 1999 and 2000.

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TABLE 3 Estimated effects of droughts on crop production, yield, and acreage.

	Maize	Rice	Soybean	Groundnut	Pigeon pea	Beans	Cowpea	Cassava	Cotton	Tobacco
Production change (%)										
Angola	−61.1	5.1	−14.7	−51.8	NA	−65.2	NA	−24.5	NA	5.6
Botswana	−67.7	NA	NA	−8.4	NA	NA	NA	NA	2.4	NA
Lesotho	−48.3	NA	NA	NA	NA	−51.1	NA	NA	NA	NA
Madagascar	−3.0	−3.5	−5.7	1.5	NA	−9.7	−2.6	0.1	−20.1	37.8
Malawi	−41.2	−25.8	−29.5	18.8	−8.4	55.6	0.6	12.9	11.1	5.2
Mozambique	−46.0	−62.4	NA	18.0	NA	24.3	116.6	−18.8	66.7	−22.2
Namibia	−41.9	NA	NA	−11.6	NA	−10.3	NA	NA	NA	NA
South Africa	−47.2	0.1	−21.2	−29.9	NA	−15.2	1.8	NA	38.5	63.9
Eswatini	−43.2	−20.0	NA	−23.1	NA	−56.2	−1.0	NA	−67.4	30.2
Zambia	−39.3	−16.9	−12.7	−3.6	NA	NA	NA	−5.2	−12.9	−34.2
Zimbabwe	−56.6	6.0	−46.9	−51.4	NA	268.4	NA	15.8	−30.2	−47.9
Yield change (%)										
Angola	6.5	−6.0	−66.4	−37.6	NA	−53.3	NA	−30.4	NA	5.2
Botswana	−25.8	NA	NA	−9.6	NA	NA	NA	NA	NA	NA
Lesotho	−30.8	NA	NA	NA	NA	−52.2	NA	NA	NA	NA
Madagascar	−3.5	−3.6	−26.9	1.1	NA	−9.6	−0.4	0.1	NA	−18.3
Malawi	−45.5	−32.7	−26.4	−9.9	−16.7	0.3	2.2	42.2	NA	−7.1
Mozambique	−37.7	−75.3	NA	−12.7	NA	4.4	81.5	37.8	NA	−4.9
Namibia	−27.3	NA	NA	−10.6	NA	−3.2	NA	NA	NA	NA
South Africa	−35.2	11.1	−25.0	−14.6	NA	−29.7	0.3	NA	NA	3.2
Eswatini	−29.5	−24.7	NA	−17.8	NA	−35.8	−2.5	NA	NA	−10.9
Zambia	−21.4	5.4	6.6	8.6	NA	NA	NA	−1.3	NA	20.6
Zimbabwe	−58.2	−8.4	−34.5	−38.2	NA	1.2	NA	3.2	NA	−41.5

Food price change (%)								
	FPI base	FPI 2016	CPI base	CPI 2016	Defl. FPI base	Defl. FPI 2016	Price ch. (%)	Food insecure pop (%)
Angola	97.33	141.67	0.68	0.47	66.65	66.45	−0.29	2.6
Botswana	95.55	99.43	0.78	0.73	74.11	72.77	−1.80	2.6
Lesotho	131.81	156.48	0.81	0.74	107.00	115.51	7.95	32.2
Madagascar	321.74	384.34	0.77	0.67	247.63	258.23	4.28	4.6
Malawi	149.42	230.92	0.49	0.33	72.66	75.70	4.19	35.9
Mozambique	74.70	100.00	0.82	0.67	61.24	67.43	10.10	6.9
Namibia	111.31	130.25	0.80	0.73	89.28	94.67	6.04	29.4
South Africa	82.26	96.40	0.80	0.79	65.99	76.45	15.85	25.6
Eswatini	109.05	130.69	0.78	0.68	84.52	89.49	5.88	47.5
Zambia	136.10	183.34	0.76	0.59	104.04	107.99	3.79	5.9
Zimbabwe	96.91	90.62	0.92	0.96	89.04	86.67	−2.66	25.2

Sources: For crop yield penalties, computations from authors using data on production and harvested area from FAOSTAT (2018); yield/acreage penalty = % change in yield/acreage in drought years relative to non-drought years; for Angola, drought year is 2012; non-drought years are 2010/11; for Botswana, drought years are 2001, 2002/3, 2007/8; non-drought years are 2005/6; for Lesotho, drought years are 2007/8 and 2012; non-drought years are 2000/1; for Madagascar, drought year is 2000; non-drought year is 1999; for Malawi, drought years are 2004/5 and 2002; non-drought years are 1999/2000; for Mozambique, drought year is 2012; non-drought year is 2011; for Namibia, drought year is 2013; non-drought years are 2010/2012; for South Africa, drought years are 2006/7; non-drought years are 2008/9; for Eswatini, drought years are 2001/4; non-drought years are 1999/2000; for Zambia, drought years are 2002 and 2005; non-drought years are 2006/7; for Zimbabwe, drought years are 2005, 2007/9, and 2012/13; non-drought years are 2000/1.

NA = not applicable.

For price effects, computations from authors using data on food price indices and consumer price indices from FAOSTAT (2018).

FPI, Food Price Index; CPI, Consumer Price Index; Base, base year; for all countries, it is 2014 except Madagascar (base year = 2013).

Price ch. = Price change from drought = ((Defl. FPI 2016 – Defl. FPI base)/ (Defl. FPI base))*100; Defl. FPI base = (FPI base)*(CPI Base); Defl. FPI 2016 = (FPI 2016)*(CPI 2016).

Food insecure pop (%) = percentage of population which was food insecure by June 2016 after 2 consecutive drought years; data on number of food insecure people is from Southern African Development Community (2016) and population data is from World Bank (2018).

population and income growth; these trends are derived from the Shared Socio-economic Pathways (SSP) (O'Neill et al., 2014). For this study, SSP4 is used; it involves moderate but unequal economic and population growth across all countries (Robinson et al., 2013). IMPACT uses input data on crop yields, irrigated water availability, population and income growth to project agricultural production, consumption, and trade. These results are further analyzed to project food and nutrition security outcomes (Figure 2).

In IMPACT, legumes such as soybean and groundnut are classified between traded and non-traded. Traded legumes can be exported and their prices vary with global markets. Non-traded legumes are entirely allocated to domestic processing and are priced based on national supply and demand. The pricing system for non-traded legumes can be considered as that of a contract farming system where prices are delinked from world markets. For this study, exogenous databases in IMPACT 3.2 were adjusted to reflect the increase of 25% in maize and soybean production in SSA between 2005 and 2011.

3.2 Incorporating drought effects into the IMPACT model

The yield and acreage penalties from drought were incorporated into the IMPACT model as exogenous shocks to crop yields and/or acreage for drought years (Figure 2). For each country, crop acreage would be reduced by an exogenous rate, "*ap*" under drought. Then, the following year, crop acreage would be returned to trend using Equation (1):

$$AR_{c,cty,t+n} = \frac{1}{1 + AP_{c,cty,t}} \tag{1}$$

Where:

$AR_{c,cty,t+n}$= area recovery rate which brings crop acreage back to trend for commodity "c" in country "*cty*" at year "*t*" plus the number of drought years "*n*"; "*n*" = 1, 2…, "*n*" consecutive drought years.

$AP_{c,cty,t}$ = acreage loss brought by drought for commodity "*c*" in country "*cty*" during year "*t*".

The same approach is used for incorporating yield loss from drought into the IMPACT model. After the drought year, crop yield is brought back to trend using Equation (2):

$$YR_{c,cty,t+n} = \frac{1}{1 + YP_{c,cty,t}} \tag{2}$$

Where:

$YR_{c,cty,t+n}$= recovery rate which brings yield back to trend for commodity "*c*" in country "*cty*" at year "*t*" plus the number of drought years "*n*"; "*n*" = 1, 2…, "*n*" consecutive drought years.

$YP_{c,cty,t}$ = yield loss from drought for commodity "*c*" in country "*cty*" during year "*t*".

In IMPACT, only the yield and acreage losses (Table 1) from drought were used. For example, the positive yield increase for Angola was not inputted as an exogenous shock in the model; similarly, the positive acreage changes for Malawi and Madagascar were not inputted into the model (Table 1). It can be safely assumed that the yield and acreage losses are mainly caused by drought, an external physical event. However, positive yield and acreage losses are mainly influenced by socio-economic factors, including relative price changes; hence, they can be considered as an indirect effect of drought. An optimization model such as IMPACT should be able to capture the indirect effects of droughts. In IMPACT, food production units for each country are defined relative to water basins and it is assumed that farmers in each food production units allocate land and other inputs across agricultural commodities depending on relative output prices. In the model, consumer demand for food is dependent on population growth and preferences which vary and change over time based on income changes. IMPACT solves for long-run optimal international trade through the following Equation (3) expression (Robinson et al., 2015):

$$\sum_{cty=1}^{n} NX_{c,t,cty} = 0 \tag{3}$$

Where:

$NX_{c,t,cty}$= net exports in thousand metric tonnes for country "*cty*" and commodity "*c*" for year "*t*".

The annual solution on international trade generates world and national price signals which are used to project long-run agricultural production and food consumption. Net exports defined as a function of production, demand, and stocks is written in Equation (4):

$$NX_{c,t,cty} = QS_{c,t,cty} - QD_{c,t,cty} - QSt_{c,t,cty} \tag{4}$$

Where:

$QS_{c,t,cty}$= annual production of commodity "*c*": by country "*cty*" for year "*t*".

$QD_{c,t,cty}$ = annual consumption of commodity "*c*" by country "*cty*" for year "*t*".

$QSt_{c,t,cty}$ = annual stock of commodity "*c*" by country "*cty*" for year "*t*".

The projections on national food production and consumption are then used to estimate food security using the equations and coefficients derived from Fischer et al. (2005). More specifically, the share of people at risk of hunger is defined through Equation (5):

$$SR_{cty,t} = 288.16 + 89.63 * \left(RC_{cty,t}\right)^2 + \left(-319.69\right) * \left(RC_{cty,t}\right) \tag{5}$$

Where:

$SR_{cty,t}$ = share of the population which is at risk of hunger for country "*cty*" and for year "*t*".

$RC_{cty,t}$ = relative kilocaloric consumption in country "*cty*" in year "*t*".

And where relative caloric consumption is in Equation (6):

$$RC_{cty,t} = \frac{C_{cty,t}}{MC_{cty,t}} \tag{6}$$

Where:

$C_{cty,t}$ = average caloric consumption in country "*cty*" for year "*t*".

$MC_{cty,t}$= minimum caloric consumption in country "*cty*" for year "*t*".

As a process-based modeling framework which assess long-run trends for "what if" scenarios, IMPACT cannot be used to estimate

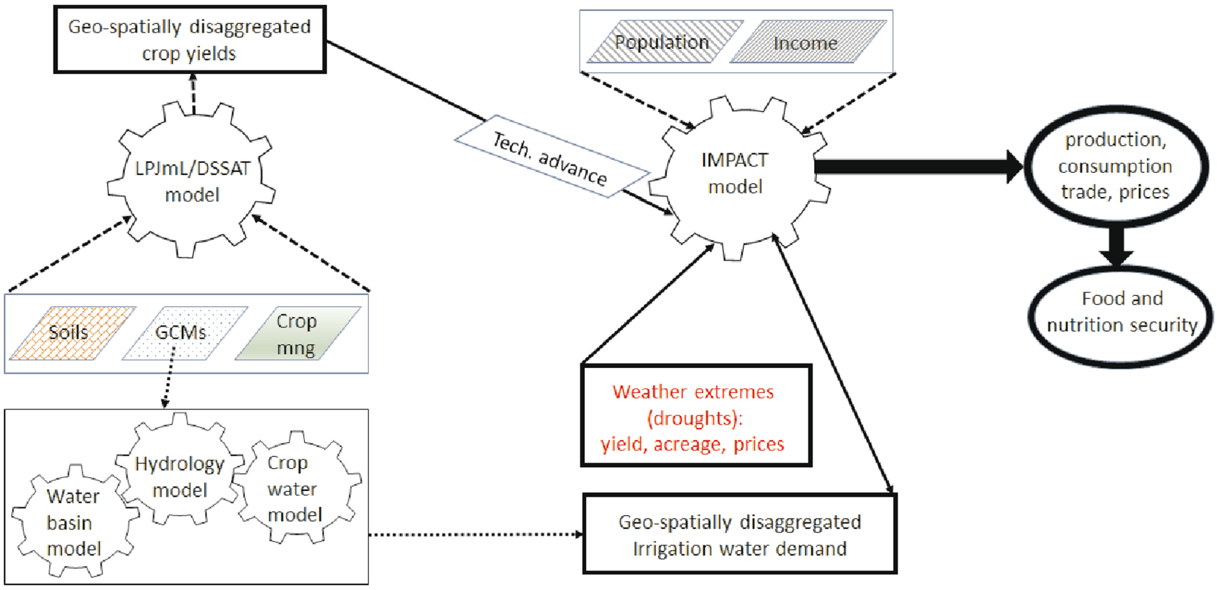

FIGURE 2
Structural framework used to project drought effects. Source: authors' illustration using Robinson et al. (2015) and Islam et al. (2016).

multiple solutions for a single scenario. Hence confidence intervals on projected estimates cannot defined with IMPACT, unlike what could be done with purely statistical models.

In IMPACT, the price effect caused by drought is inputted as an additional markup on national food prices (Figure 2). In a drought year, the marketing margin for national food prices were adjusted upward by a coefficient, "*pp*", reflecting the change in food prices brought by drought as estimated in Table 3. For Angola and Botswana, where food prices slightly decrease under drought, no price shock was inputted into IMPACT. For Zimbabwe, the drought price effect used is the same as that of its major food trade partner, South Africa. For each country, the food price effect brought by drought was applied to all food commodities irrespectively. Given that yearly prices are endogenously estimated in IMPACT, no recovery rate is applied to prices in non-drought years unlike what is done for crop yields and acreage. When a country is faced with consecutive droughts, the price effect from drought is multiplied by two for the second consecutive year and by 'n' for the n^{th} consecutive drought year. In addition, when drought decreases regional maize production by more than 21%, the price increase from drought is also applied to all countries in IMPACT to reflect regional food scarcity. The 21% threshold reflects the regional production difference in 2015 and 2016 (2-year consecutive drought) compared to 2010 and 2011 which are also two years characterized by no drought across the whole region (Table 2).

The frequency of reported droughts per country (Table 2) between 2000 and 2016 was used to project future occurrences of drought. For example, if there were two reported droughts in any given country between 2000 and 2016, the drought frequency would be 11.8%; this frequency was then multiplied by 16, the number of years between 2020 and 2035, to project the number of future incidences of drought. Drought years were then randomly selected to match the projected number of droughts between 2020 and 2035 (Table 4). Based on the projected drought events, all countries except South Africa and Angola would experience at least two consecutive drought events between 2025 and 2040. For each drought year in a country, the corresponding price increase was also estimated. For example, Mozambique is projected to experience drought in 2027 (Table 4); that year, food prices across the country would increase by 10%. The next year, droughts would reduce regional production by at least 25%. Hence, Mozambique would again experience an increase in food prices even if the country itself would not experience drought (Table 4).

In IMPACT, tobacco is bundled with "other crops" for all countries. However, for Malawi, Zimbabwe and Zambia, tobacco dominates "other crops" in the IMPACT model. For these countries, production values for 'other crops' in the base year (three-year moving average for 2005) in the model are very similar to the three-year moving average tobacco production for 2005, based on FAOSTAT: the difference is less than 15%. Hence, in this study, it is assumed that drought affects tobacco production in Malawi, Zimbabwe, and Zambia; these three countries accounted for 73% of tobacco production in southern Africa between 2004 and 2006.

One limitation of the methodology is that IMPACT, as a partial equilibrium model, does not capture the indirect effects of droughts on the industrial and service sectors; it only focuses on the agricultural sector. For countries which depend heavily on agriculture, droughts are likely to negatively affect the industrial and service sectors. The compounding effects of drought on these sectors should further worsen food insecurity; some of these effects are captured through the observed price effects used in this study (Table 4). However, these observed price effects are also reflecting the impact of policy measures which were deployed in each country toward disaster management. As such, the simulated results from IMPACT on the effect of droughts on the number of people at risk of hunger is likely to be underestimated for some countries.

4 Results: projected droughts effects in southern Africa

4.1 Baseline results: projections on food production, food consumption, and food security in southern Africa under a scenario involving moderate economic growth and no drought

This section shows how changes in population and income will influence production and food security in southern Africa by 2040. The section highlights the importance of non-climate drivers, such as population and income changes, in influencing food security in the region. The results in this section also serve as a baseline to assess the impact of droughts in southern Africa over the same time frame (2010 to 2040).

4.1.1 Projections on *per capita* consumption under the 'no drought' scenario

Per capital food consumption is projected to increase across southern Africa by 2035, assuming moderate but unequal growth in *per capita* incomes. Across the region, stimulant consumption would experience the highest increase followed by meat, fruits, pulses, vegetables, and cereals (Figure 3A). The rise in meat consumption would be reflecting the impact of rising incomes as *per capita* consumption of all meat products including pork, poultry, lamb, and beef would substantially rise (Figures 3A,B).

Per capita consumption of cereals would increase by a little more than 10% between 2010 and 2040. Maize would still dominate cereal consumption by 2035 followed by wheat and rice each of which would still account for more than 10% of cereal consumption (Figure 3C). *Per capita* consumption of wheat would not change between 2010 and 2035; for maize and rice, consumption would increase by about 15 and 20%, respectively (Figure 3C). Among these three cereals, only maize would experience substantial changes in utilization. In 2010, the share of maize consumed as food was about 70% whereas 25% of all consumed maize was allocated to animal feed (Figure 3F). By 2035, these values would change to about 60% for food and 35% for animal feed, reflecting the positive impact of rising incomes on the demand for livestock-based products. For rice and wheat, utilization patterns would not change substantially between 2010 and 2035, as these two cereals would still be primarily consumed as food in 2040 (Figure 3F).

For root and tubers, *per capita* consumption in southern Africa would not change much between 2010 and 2040. In 2010, cassava and potato dominated the consumption of roots and tubers, each accounting for more than 10% of consumption. In 2040, the same two products would still dominate consumption. Cassava alone would still be accounting for more than 60% of the consumption of roots and tubers, but its utilization would change between 2010 and 2040, with a reduction in the share allocated to animal feed and an increase in the shares allocated to food and other uses. This would partly stem from the rising income inequalities between countries which would push the poorer countries toward increasing their consumption of cassava as food. A similar trend would be observed for sweet potato (Figures 3A,D,F).

By 2040, the consumption of vegetable oils would still be dominated by palm oil, soybean oil, sunflower oil, and other oils (Figure 3E). Palm oil would experience an increase of about 1.5% in *per capita* consumption whereas the consumption of soybean and sunflower oils would decrease by about 5 and 20%, respectively (Figure 3E). Overall, *per capita* consumption of vegetable oils (processed oils) would decrease by 5% (Figure 3A). For sugar, regional *per capita* consumption would decrease by about 5% also (Figure 3A). For pulses, regional *per capita* consumption would increase by about 25% between 2010 and 2040 (Figure 3A); such increase would be associated with an increase in *per capita* consumption in all countries although for some countries the increase would be less than 5% whereas in others, it would be much higher (Figure 3A).

4.1.2 Projections on aggregate food consumption, production, and net trade under the 'no drought' scenario

At a regional level, meat consumption would increase by about 110% between 2010 and 2040. This commodity along with vegetables, fruits and pulses would experience the highest consumption change over time after stimulants. Cereals would follow with an increase of about 90%. Egg consumption would experience the smallest consumption change with a value of 55% (Figure 4A).

By 2040, food production too would have increased in the region thanks to technological advancement in agriculture. However, such growth would be slower compared to the growth in food demand (Figure 4A). The production of meat, stimulants, pulses, and fruits would change by about 100%, each. The region would become more import-dependent for its key staple food groups, namely cereals, roots & tubers, vegetable oils and meat. The region which was self-sufficient for roots & tubers in 2010 would be importing about 15% of its consumption requirements by 2040 (Figure 4B). For fruits and sugar, the region would remain a net exporter by 2040.

The higher reliance on food imports would be partially caused by low crop productivity coupled with small changes in crop area in southern Africa. For example, maize is currently grown in all countries in southern Africa whereas cassava, which is consumed in all countries, is only grown in 6 countries, namely Angola, Madagascar, Malawi, Mozambique, Zambia, and Zimbabwe. The maize and cassava acreages are projected to increase by 16 and 13% respectively, between 2010 and 2040. Similarly, cassava yield would increase by 21% whereas maize yield would increase by 49%. The growth in acreage and yield would not be enough to ensure that production keeps pace with demand (Figure 4C).

For vegetable oils, the picture is mixed. Acreage for sunflower would decrease over time and yields would increase by less than 50%. Hence, total production would increase by 25% for nontraded sunflower; it would reduce by −1% for traded sunflower. Acreage would decrease for non-traded soybean and would barely change the same for traded soybean. However, yields would improve substantially and especially in South Africa and Zambia. Hence, regional soybean grain production would increase substantially between 2010 and 2040 (Figure 4C).

All countries would be producing beef, poultry, and pork by 2040. The animal population would increase for beef, poultry, and pork, although it would increase more for poultry. Yields would also increase for all three meat commodities, although the increase would be smaller for beef compared to poultry and pork. Poultry production would more than double, but this would not be the case for the other meat-based commodities. Hence, total meat production would less than double compared to demand (Figures 4A,C).

4.1.3 Projections on food security under the 'no drought' scenario

At the regional level, the number of people at risk of hunger would increase by about 30% between 2010 and 2040 to reach about 53 million people in 2035 (Figure 5A). All countries would experience an increase in the number of people at risk of hunger except for the wealthier countries like Botswana, South Africa, and Namibia which would experience a reduction in the number of people at risk. In relative terms, food security would improve slightly, as the regional share of the population at risk would decrease slightly from 23% in 2010 to 20% in 2040 (Figure 5B). The share of people at risk would decrease for all countries except Eswatini which would experience an increase of about 2 percentage points. Poorer countries which would register slight reductions (less than 5 percentage points) in the share of their population at risk consist of Malawi, Lesotho, and Angola.

4.2 Projected impacts of recurrent droughts in southern Africa under moderate economic growth

4.2.1 Impact on production

The recurrent droughts would affect agricultural production which would become much more erratic (Figures 6A–J). Maize would experience the largest reduction in production under drought when compared to other food crops. For example, with the projected drought in 2025, regional maize production would decrease by about 25% compared to a scenario involving no drought (Figure 6A). For all other crops, the change in production in 2025 would range between −8 and 5% (Figures 6B–J). Across all years, cowpea, a drought-tolerant pulse, would experience the largest increase in production under the scenario involving recurrent droughts. More specifically, regional cowpea production would rise by close to 20% in the years when Malawi, a major cowpea producer, would be affected by drought (Figure 6).

For oilseeds, an interesting scenario would develop that would highlight the effect of local prices being delinked from world markets; such situation can happen through contract farming when farmers' prices are fixed earlier in the season. In the model, Madagascar, Malawi, South Africa, Zambia, and Zimbabwe produce traded soybeans which can be exported. In addition, South Africa, Zambia, and Zimbabwe produce non-traded soybean which is entirely allocated to domestic uses and for which prices are only defined through local supply and demand. Traded groundnut is produced in all countries except Lesotho; for nontraded groundnuts, non-producing countries are Lesotho, Namibia and Eswatini. In 2030, three of the largest maize producers in the region would experience a drought: South Africa, Malawi, and Mozambique. This would lead to the highest regional food price hike experienced in the region due to drought between 2025 and 2040. In South Africa, maize production would decrease by 46% in 2030 under the scenario involving droughts compared to the scenario involving no drought (Table 5). This reduction in production would be linked to a reduction of about 32% in yield and 20% in acreage for maize. The freed acreage would be allocated to more profitable crops less affected by the drought. In this case, such crops would turn out to be pulses and nontraded oilseeds. Nontraded soybean and groundnut would experience the largest increase in producer price under drought, reflecting that the demand response to shocks is usually more inelastic for nontraded compared to traded commodities. In addition, the producer price increase for nontraded oilseeds would be higher for soybean than that for groundnut; this would be caused partly by soybean becoming scarcer due to the higher negative impact of drought on soybean compared to groundnut yields in South Africa. The higher increase in the producer price for nontraded soybean would translate into the highest increase in the acreage allocated to this commodity. Nontraded groundnut would follow with an acreage increase of 36%. Hence, nontraded soybean and groundnut production would increase by 58 and 22%, respectively (Table 5). This would translate into an increase of about 21% in total soybean production in South Africa and an increase of about 15% at the regional level (Figure 6).

Another interesting development relates to cassava production which would not increase when there is drought. This result reflects that cassava is not a preferred food in the region nor is it considered a cash crop unlike oilseeds and selected pulses. The highest reduction in cassava production would occur in 2026 and 2027 when Angola, the largest cassava producer in the region, would be experiencing two consecutive droughts. By 2027, maize production in Angola would decrease by 71% with an associated acreage reduction of 22% (Table 5). Here too, the freed acreage would be allocated to more profitable crops less affected by drought. In this case, cotton would experience the highest increase in acreage, followed by tobacco, rice (18%), and nontraded groundnuts (18%). Cassava's yield would be negatively affected by drought in Angola, although less severely compared to maize. More specifically, cassava's yield would decrease by 30% in 2027 compared to a reduction of 63% for maize (Table 5). Some of the land freed from maize and other crops would be allocated to cassava which would experience an increase of about 5% in acreage. All in all, cassava production would decrease by 27% in 2027, after two years of consecutive droughts. In 2027, other cassava-producing countries would also experience drought, namely Madagascar, Mozambique, and Zimbabwe. Mozambique would reduce its cassava production by 32% whereas Madagascar and Zimbabwe would increase their cassava production by 3 and 19%, respectively. Hence, regional cassava production would decrease by 20% (Figure 6).

Apart from cowpea and soybean, another crop which would experience an increase in production under drought is bean although, for some years, regional bean production would be smaller under the scenario involving recurrent droughts compared to the scenario involving no drought. For example, with the scenario involving recurrent droughts, bean production would be lowest in 2027, a year when drought would affect two key bean producers (Angola and Madagascar) accounting for 50% of regional production. Angola would experience a reduction of 71% in bean production (Table 5) whereas for Madagascar, the reduction would be smaller (around 14%), since bean is less affected by drought in this country (Table 3). Regional bean production under drought would be highest in 2031, 2032, and 2037 when production would be around 7% higher under the scenario involving recurrent droughts compared to the one involving no drought. In 2031, none of the key bean producers, namely Angola, Madagascar, Malawi, and South Africa would experience a drought. However, Zimbabwe which accounts for 10% of regional bean production, would experience a drought which would lead to reduction in national maize production (−59%) and an increase in bean

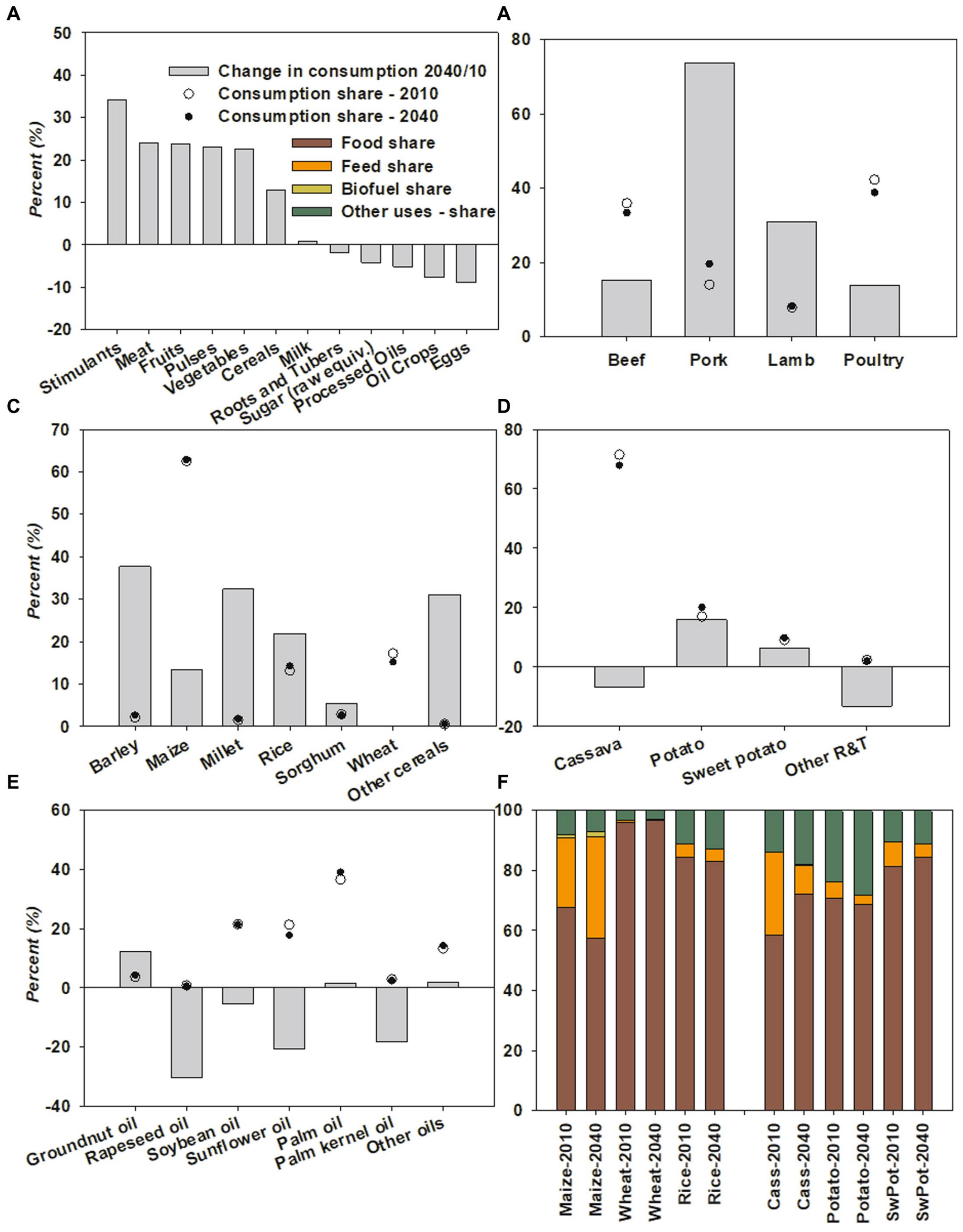

FIGURE 3
Projected changes in consumption patterns in southern Africa under the 'no drought' scenario - 2040 versus 2010 (%); **(A)** Food groups; **(B)** Meat; **(C)** Cereals; **(D)** Starchy roots; **(E)** vegetable oils; **(F)** use shares for selected cereals, roots and tubers Source: authors' computations using results from IMPACT3.2.

production (96%). The bean production increase in Zimbabwe would translate into an increase in regional bean production for 2031.

4.2.2 Impact on food security

Under a scenario involving no drought, the volume of net maize exports out of southern Africa is projected to slightly decrease between 2025 and 2040. However, recurrent droughts would introduce more volatility in maize trade and make it difficult for policy-makers to adequately respond to droughts. Drought would also reduce regional maize consumption by eroding the purchasing power for maize through higher consumer prices and/or reduced incomes. As a result, net maize exports would in general be smaller in volume compared to a scenario involving no drought (Figure 6K). In addition, the region would find itself importing maize whenever South Africa, the largest maize producer and exporter in the region, would be hit by a drought (Figure 6K; Table 4).

By reducing food availability and consumption, droughts would worsen food insecurity across southern Africa. The highest increase in the number of people at risk would occur in 2030 (Figure 7A), the year

TABLE 4 Projected drought events and drought price effects across southern Africa between 2025 and 2040.

	'25	'26	'27	'28	'29	'30	'31	'32	'33	'34	'35	'36	'37	'38	'39	'40
Drought events																
Angola		d	d													
Botswana	d	d			d		d	d				d		d		d
Lesotho		d	d				d	d	d		d	d			d	
Madagascar			d									d		d		d
Mozambique	d		d			d	d				d					
Malawi		d				d		d				d	d			
Namibia								d	d		d					
Eswatini	d					d		d	d	d		d				d
South Africa	d			d		d						d				d
Zambia							d	d								
Zimbabwe	d		d	d	d		d		d		d				d	
Drought price effects (%)																
Lesotho	11	16	24	8		13	16	24	32		8	16			8	
Madagascar	6		4	4		7						6		4		4
Malawi	6	8		4		7		4				5	8			
Mozambique	13		10	10		16	20				10	10				
Namibia	8			6		10		6	12		6	8				
Eswatini	8			6		10		6	12	18		8				6
South Africa	21			16		26						20				16
Zambia	5			4		6	8	11				5				
Zimbabwe	21		16	32	48	26	32		16		16	20			16	

Source: for price effects, authors' computations from estimates in Table 3. Regional price increases occur in 2025, 2028, 2030, and 2036. In these years, regional maize production without the price effects decreases by 28, 25, 34, and 28%, respectively, (reductions are higher than 21% threshold). Hence, the national price increases for 2025, 2028, 2030, and 2036 are 34, 18, 62, and 31% higher than those in Table 3.

characterized by the highest decrease in regional maize production. Across all years, the countries which would experience the highest increase in the number of at-risk people would be Mozambique and Zimbabwe. In 2031, Mozambique would experience a second consecutive drought year and the number of people at risk of hunger would reach 1.9 million people. In Zimbabwe, following three consecutive drought years, the number of people at risk of hunger would be highest in 2029 with 1.7 million people (Figure 7A).

In terms of percentage change, Lesotho, a country with a small population, would experience the largest increase in the number of people at risk under droughts. In 2030, the regional maize shortage would lead to an increase of 26% in the number of people at risk in this country (Figure 7B). However, from 2031, three consecutive drought years would follow in the country such that by 2033, there would be an increase of 76% in the number of people at risk compared to a scenario involving no droughts. Other countries which would experience substantial relative increases in the number of people at risk include South Africa, Zimbabwe, Namibia, Mozambique, and Eswatini. South Africa would experience the largest proportional increase in the number of people at risk of hunger in 2025 when the country would experience an increase of about 60% in the number of people at risk of hunger compared to a scenario involving no droughts Figure 7B).

4.3 Projected impacts of two-year consecutive regional droughts in southern Africa under moderate economic growth

In this section, an analysis is done on the impact of droughts with a longer duration given that such droughts are projected to increase in the future in southern Africa. More specifically, projected future drought occurrences are re-arranged to generate regional two-year droughts like the ones experienced in 2014/15 and 2015/16 in southern Africa. In this case, maize would experience extremely large reductions compared to other crops. For example, maize production would decrease by more than 40% in 2027. With Zambia among the countries that would experience consecutive droughts in 2026, regional maize production would decrease by 38 and 42% in 2026 and 2027, respectively. By contrast, tobacco's maximum production loss would reach about 15% and would occur in 2028, 2029, 2031, and 2032. For cotton, the maximum production loss caused by drought would occur in 2029 with a value of about 20%. Crops which would experience significant increases in production during the regional consecutive drought years are cowpea, soybean and, to a lesser extent, bean (Figure 8).

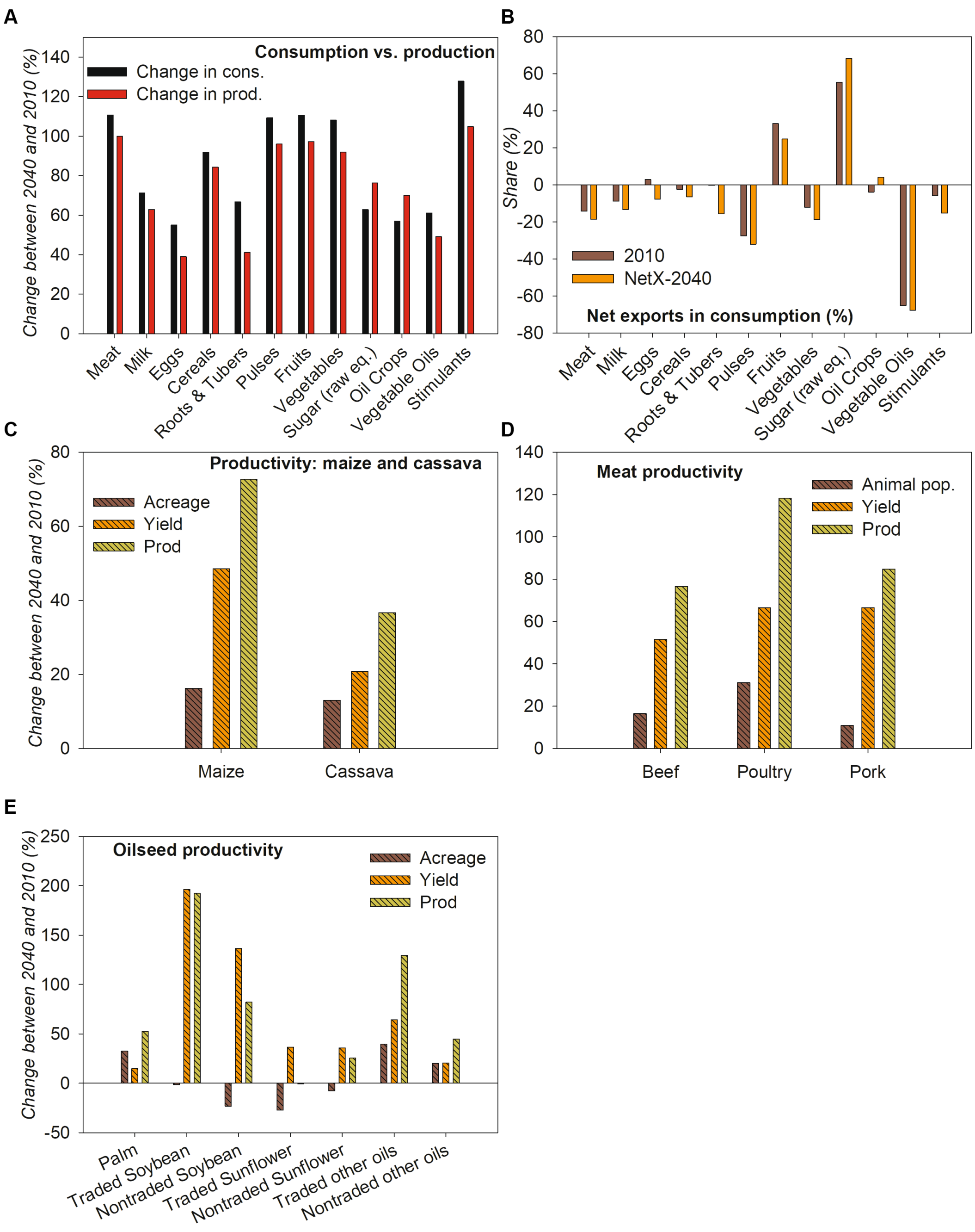

FIGURE 4
Projected production and consumption changes in southern Africa under the 'no drought' 928 scenario - 2040 versus 2010; **(A)** consumption versus production changes; **(B)** changes in the share of net exports in consumption; **(C)** changes in maize and cassava productivity; **(D)** changes in meat productivity; **(E)** changes in oilseeds productivity Source: authors' computations using results from IMPACT 3.2.

The impact of the regional consecutive droughts on food security would be substantial. The minimal number of people at risk due to the regional recurrent droughts would be more than 6 million in 2027. Countries which would experience substantial increases in the number of people at risk would consist of Zimbabwe, followed by Mozambique, Malawi, South Africa, Madagascar, and Zambia (Figure 9A).

In relative terms, among all countries, South Africa would experience the highest proportional increase in the number of people at risk; indeed, in 2027 the number of people at risk would nearly double in South Africa due to the recurrent drought. Apart from South Africa, all other countries except Angola, Botswana, Madagascar, and Zambia would experience an increase of at least 10% in the number of people at risk during the regional consecutive droughts in 2021/22 and 2026/27 (Figure 9B).

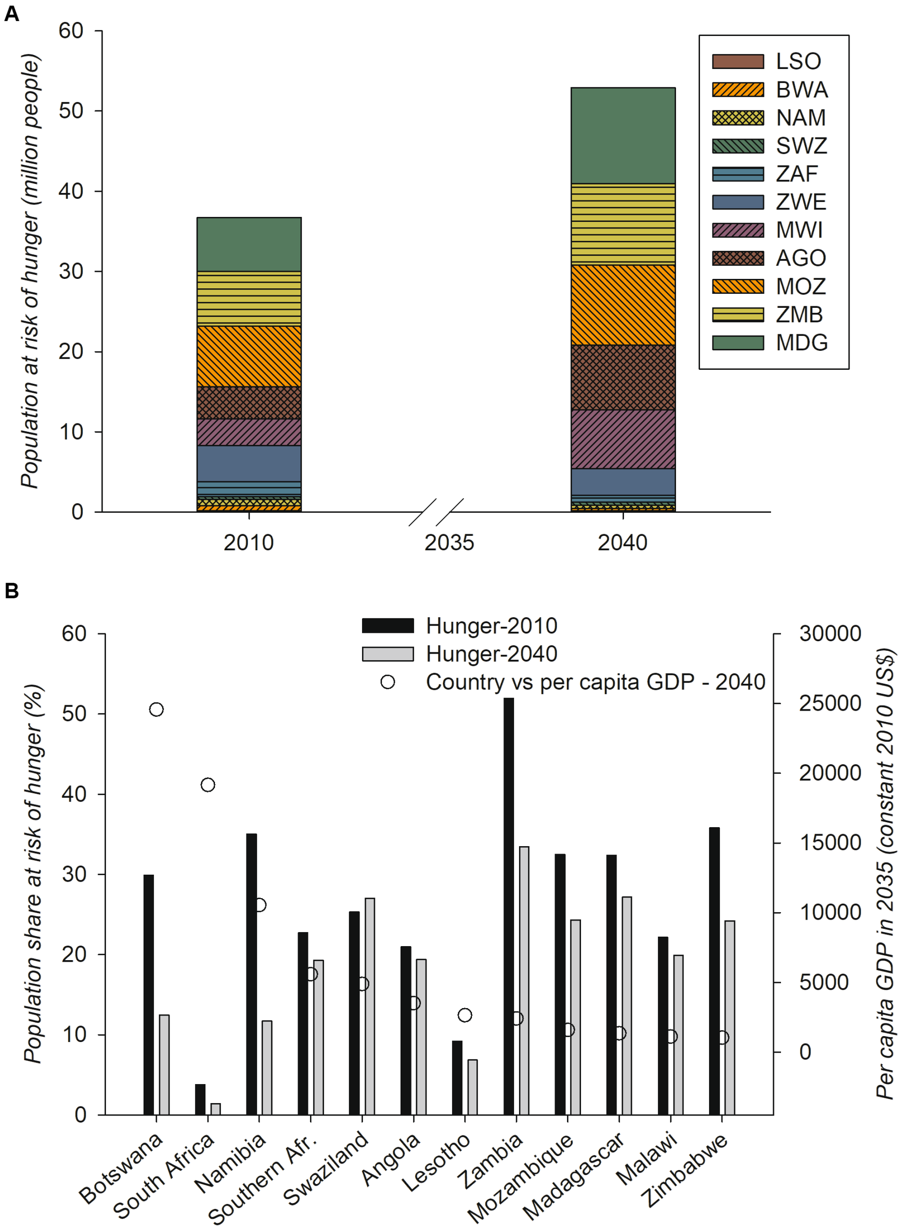

FIGURE 5
Projected change in the number of people at risk of hunger in southern Africa under the 'no drought' scenario – 2040 versus 2010; **(A)** Population at risk of hunger (million people) **(B)** Share of the population at risk of hunger (%) AGO: Angola; BOT: Botswana; LSO: Lesotho; MDG: Madagascar; MWI: Malawi MOZ: Mozambique; NAM: Namibia; S. Afr.: South Africa; SWZ: Eswatini; ZMB: Zambia; ZWE: Zimbabwe Source: authors' computations using results from IMPACT 3.2.

4.4 Model validation: projected versus reported values for production and food security under drought in southern Africa

4.4.1 Model validation: production under drought in southern Africa

To validate the model, simulated results on the impact of droughts on crop production are compared with reported data from FAOSTAT; such an approach is used to assess the ability of IMPACT at making reliable projections. In general, production changes due to drought are similar between the reported and simulated results for all countries and across all crops (Table 6). Also, the magnitudes of the changes are similar between the simulated and reported values (Table 6). Some of the discrepancies can be explained by the assumptions in IMPACT not fully reflecting the socio-economic environment affecting crop production under drought. For example, the reported values on production changes under drought suggest that farmers in Malawi do reallocate maize acreage to other crops in a drought year and also tend better to these crops such that the country even experiences an increase in the production of beans, followed by groundnuts, cassava, cotton and tobacco (Table 3). However, the same does not happen in neighboring Zambia where a different land tenure system does not

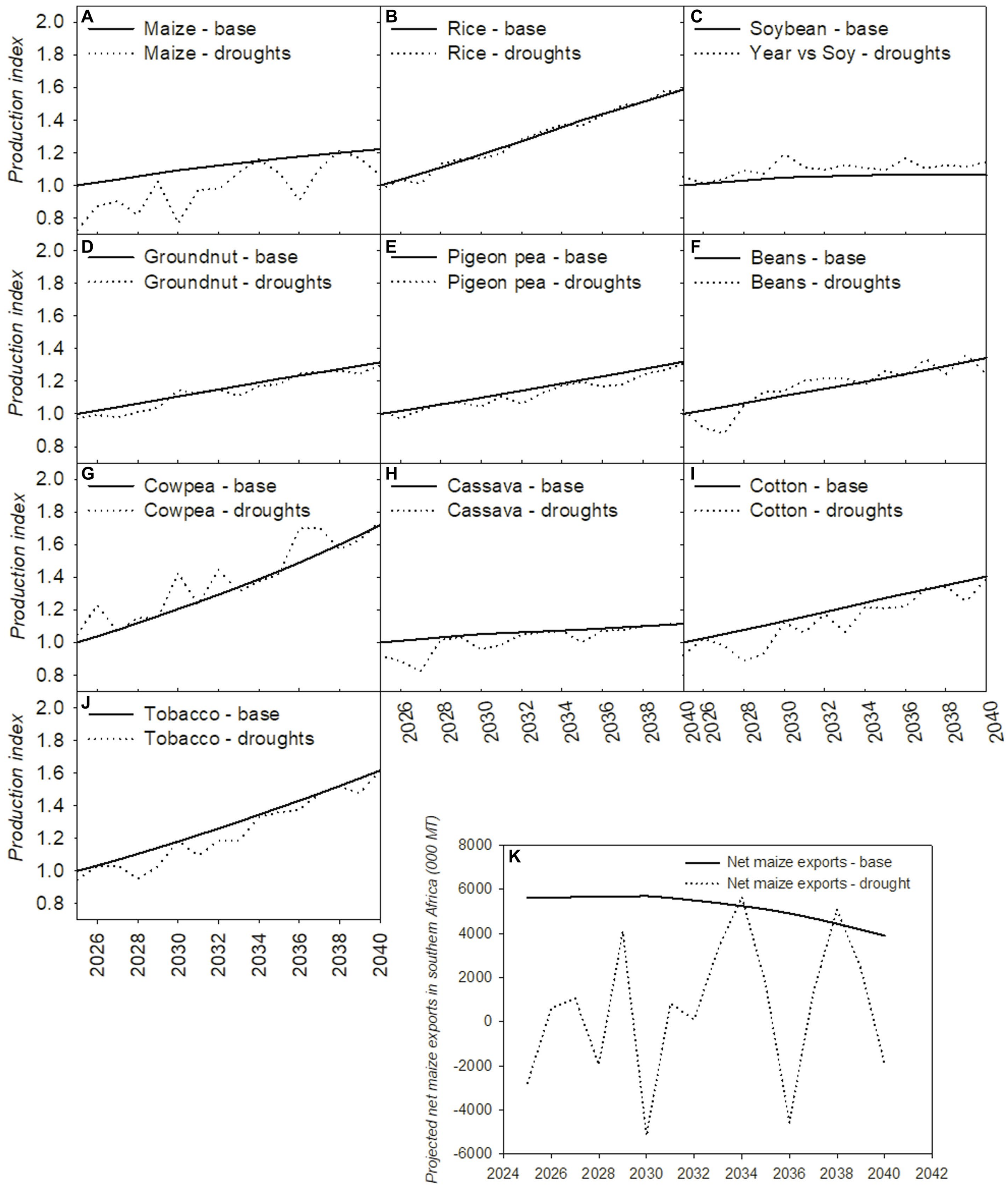

FIGURE 6
Projected impact of droughts on agricultural production and net maize exports for southern Africa; **(A)** maize; **(B)** rice; **(C)** soybean; **(D)** groundnut; **(E)** pigeon pea; **(F)** beans; **(G)** cowpea; **(H)** cassava; **(I)** cotton; **(J)** tobacco; **(K)** net maize exports Source: authors' computations using results from IMPACT 3.2.

provide farmers with the incentives to quickly adjust acreage under drought (Okori, 2018). Hence, the reported values suggest a reduction in the Zambian production of all crops in a drought year (Table 3). In the optimization model, IMPACT, it is assumed that farmers can reallocate crop acreage when faced with a drought and can also re-adjust input (labor, fertilizer, supplemental irrigation, etc.) allocation across crops. Here, IMPACT is able to simulate the behavior of Malawian farmers and implies a national increase in the production of beans, cowpea, cotton, groundnuts and tobacco in a drought year. For Zambia, the simulated results imply that the country should maintain its rice production levels in a drought year and should increase its production of cassava, cotton, and groundnuts.

TABLE 5 Bio-economic impact of drought on crop production in South Africa (year 2030) and Angola (year 2027).

	South Africa 2030 (% change caused by drought)				Angola – 2027 (% change caused by drought)			
	Yield	Acreage	Producer price	Production	Yield	Acreage	Producer price	Production
Maize	−32	−20	19	−46	−63	−22	0	−71
Rice	−7	4	18	−3	−8	18	0	8
Cassava	NA	NA	NA	NA	−30	5	0	−27
Soy-tr.	−22	0	18	−23	NA	NA	NA	NA
Soy-nontr.	−16	88	191	58	NA	NA	NA	NA
Grdnut-tr.	−12	−11	17	−22	−38	−21	−2	−51
Grdnut-nontr.	−10	36	54	22	−35	18	−3	−24
Pigeon pea	NA	NA	NA	NA	NA	NA	NA	NA
Bean	−26	−5	17	−29	−53	−40	−1	−71
Cowpea	5	16	16	21	NA	NA	NA	NA
Cotton	−1	2	0	1	0	39	0	39
Tobacco	NA	NA	NA	NA	−2	22	0	20

Source: authors' computations using results from IMPACT 3.2.

As a process-based model, IMPACT should also be well calibrated. In this study, the share of net imports in consumption for all food groups in southern Africa can be used to assess whether IMPACT is well calibrated. The observed moving average value of the share of net imports in southern Africa for different food groups in 2010 is shown in Table 1 and is derived from FAOSTAT. The simulated moving average value from IMPACT for 2010 is shown in Figure 4B. Observed and simulated 2010 values are similar, and this suggests that IMPACT is well calibrated.

4.4.2 Model validation: Food insecurity under drought In southern Africa

Simulated results on the impact of droughts on food insecurity are also compared with past reported data across southern Africa for the purposes of assessing the quality of the projected results from IMPACT. The simulated results on droughts effects on food insecurity are generally smaller than those reported across southern Africa in 2015 and 2016. For example, reported values suggest that the number of food insecure people in Malawi increased by 116% in 2015 a drought year compared to 2014 a non-drought year (Southern African Development Community, 2016). In 2016, a second consecutive drought year, the number of food insecure people increased by 395% compared to 2014 (Southern African Development Community, 2016). However, the simulated results imply that the number of people at risk of hunger in Malawi would increase by 7% in a first drought year in 2031; for a second consecutive drought year in 2032, the number of people at risk would increase by 10%. Similar results are found for Mozambique, Namibia, Zambia, and Zimbabwe. The higher reported values from SADC (2016) include people who are food insecure for reasons other than drought. In addition, droughts usually negatively affect rural incomes and most likely reduce purchasing power by a higher value than what has been used in this study. Hence, the simulated results can be considered as the lower limit on the impact of droughts on food security (Table 6).

The simulated results imply a higher increase in the number of people at risk in a second consecutive drought year compared to a first drought year. This is also the case in the reported results from SADC (2016) for most countries. In addition, the reported share of the population which was food insecure in 2016 was less than 5% in Angola and Botswana (Table 3). Such result is consistent with the results from the food price analysis which implied no food price increase in 2016 in real terms. The simulated results also imply no change in the number of people at risk due to droughts in these two countries (Table 6).

5 Discussion

The study results have illustrated how drought would jeopardize future food security in southern Africa given that for its food security, the region strongly depends on maize, a crop which is very sensitive to drought. More specifically, the study has shown that with moderate economic growth and no future droughts, food security would only slightly improve in southern Africa by 2040. In other words, the region would not become wealthy enough to produce or import enough food to eliminate food insecurity. In this context, recurrent droughts would worsen food security by severely affecting the production of maize which would remain a staple food by 2040. Indeed, compared to other food and cash crops, maize would experience the largest reduction in production under drought. With consecutive two-year regional droughts, most countries would experience an increase of at least 10% in the number of people at risk of hunger within one single year and this would have serious implications for humanitarian aid. Not much has been documented on the effectiveness of humanitarian aid in southern Africa. Most countries in southern Africa have a government department dedicated to disaster management; but they face various challenges including budgetary and technical constraints to support disaster management (Republic of Botswana, 1996; Parliament of Lesotho, 1997; Government of Zimbabwe, 2001; Parliament of the Republic of South Africa, 2002; National Assembly (Angola), 2003; King and Parliament of Swaziland, 2006; Government of Zambia, 2010; Republic of Namibia, 2012; Parliament of Malawi, 2014; Assemblee Nationale (Madagascar), 2015; Matos and Ndapassoa, 2020; Republic

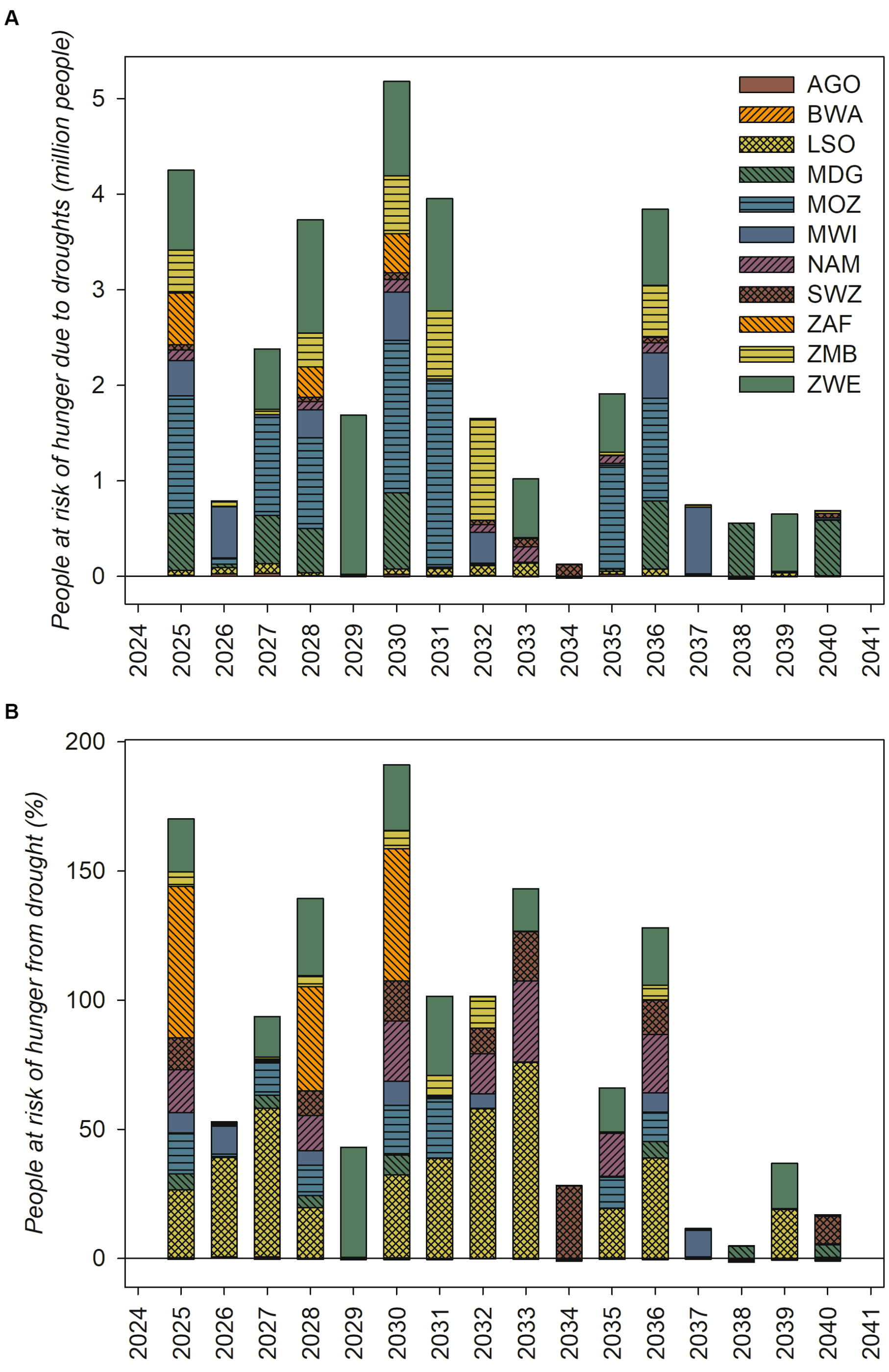

FIGURE 7
Projected impact of droughts on food security in southern Africa; **(A)** Population at risk of hunger (million people) **(B)** Share of the population at risk of hunger (%) AGO: Angola; BOT: Botswana; LSO: Lesotho; MDG: Madagascar; MWI: Malawi MOZ: Mozambique; NAM: Namibia; S. Afr.: South Africa; SWZ: Eswatini; ZMB: Zambia; ZWE: Zimbabwe Source: authors' computations using results from IMPACT 3.2.

of Mozambique, 2020). Based on the World Bank, an effective "response and reconstruction" strategy after disaster should include three components: initial response; assessment and policy making; and reconstruction (Jha et al., 2010). The initial response should last about 2 weeks after the disaster and should entail conducting a rapid needs assessment and launching an emergency response. The "assessment and policy making" component should last about 2 months after the disaster and should be closely linked to the reconstruction component. Detailed assessment needs should be conducted within the 2-month period; in addition, a reconstruction plan should be defined and approved by the government over that period. The reconstruction component should kick in at the same time as component two, but it should last longer: 2 years and above. That component should include an institutional and financial strategy; it

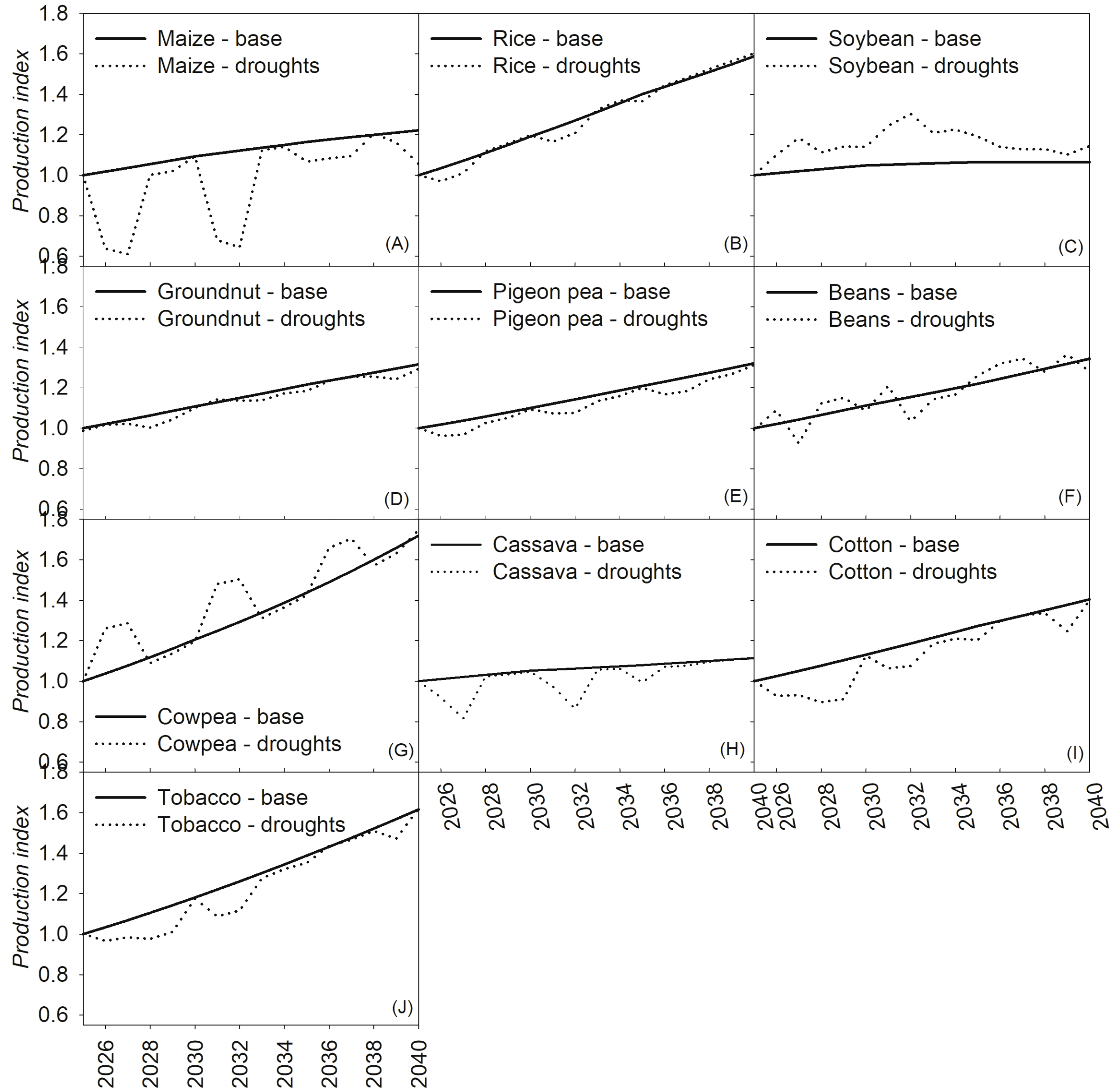

FIGURE 8
Projected impact of regional two-year droughts on agricultural production in southern Africa; **(A)** maize; **(B)** rice; **(C)** soybean; **(D)** groundnut; **(E)** pigeon pea; **(F)** beans; **(G)** cowpea; **(H)** cassava; **(I)** cotton; **(J)** tobacco Source: authors' computations using results from IMPACT 3.2.

should also include community participation in designing and implementing a reconstruction strategy. The reconstruction component should also include a risk management strategy. All activities linked to the 'response and reconstruction' strategy should also be monitored and evaluated to assess their effectiveness and inform future activities (Jha et al., 2010).

As noted in the literature, drought vulnerability is influenced by both physical and socio-economic factors (Shiferaw et al., 2014; Kamali et al., 2018). Socio-economic factors are linked to governance, demography, technological advancement, and economic development (Shiferaw et al., 2014). Some policy measures which could be used to reduce drought vulnerability in southern Africa are related to breeding for stress-resilient maize, crop diversification, and rainwater harvesting.

Enhancing food security in southern Africa under drought would call for breeding and deploying maize that is tolerant to both drought and heat stresses. International breeding efforts have led to the development of drought-tolerant maize varieties and ex post studies on have shown that these varieties perform quite well under mild or moderate drought conditions in Uganda and Nigeria (Wossen et al., 2017; Simtowe et al., 2019). However, additional efforts are required to develop improved maize varieties which are early-maturing and have some tolerance to both heat and drought stresses. Early maturity provides an effective drought avoidance strategy by completing flowering, the most sensitive stage to moisture deficit, before the onset of drought thus escaping terminal drought (Badu-Apraku and Fakorede, 2013).

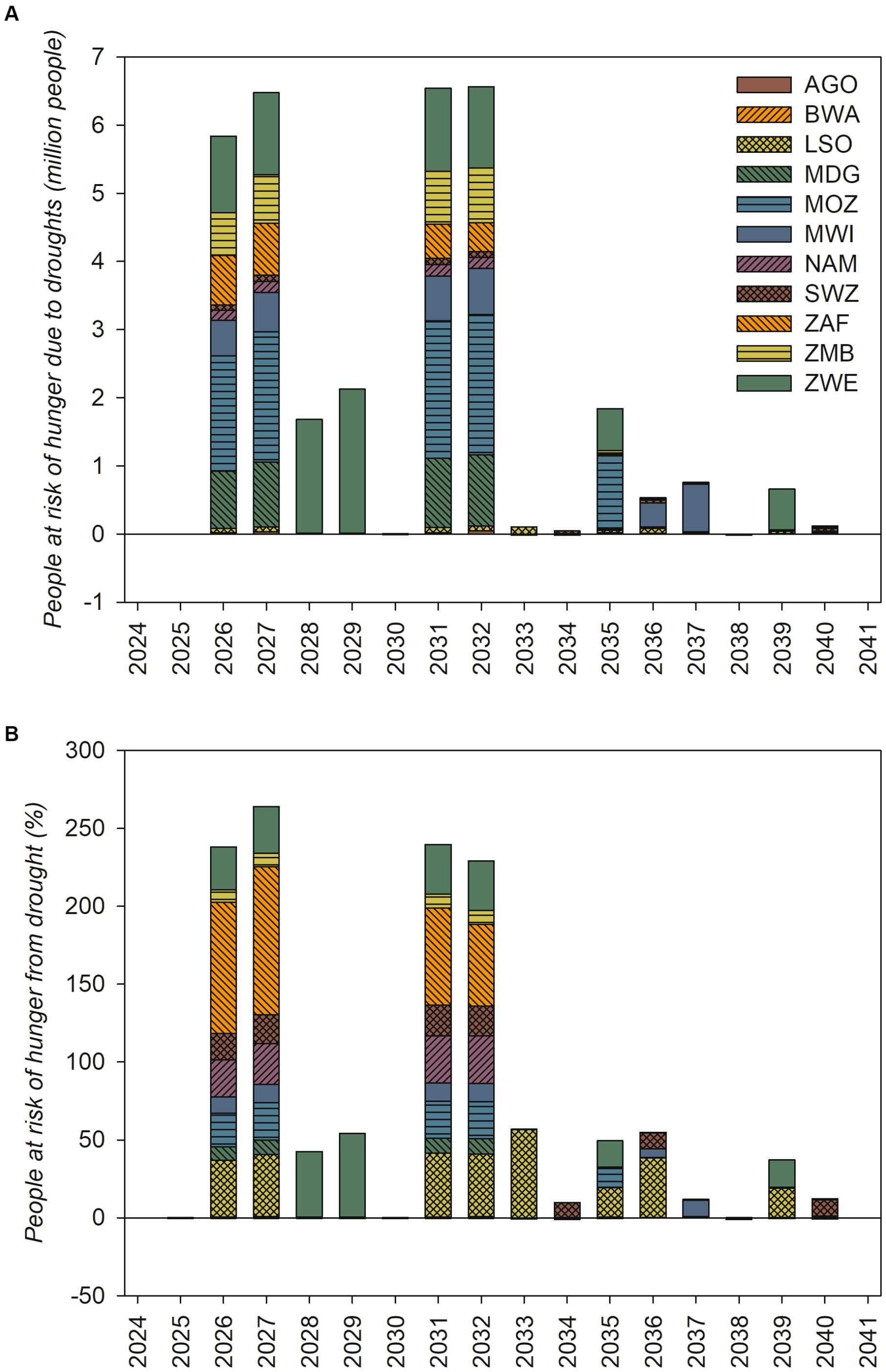

FIGURE 9
Projected impact of two-year droughts on food security in southern Africa; **(A)** Population at 957 risk of hunger (million people) **(B)** Share of the population at risk of hunger (%) AGO: Angola; BOT: Botswana; LSO: Lesotho; MDG: Madagascar; MWI: Malawi MOZ: Mozambique; NAM: Namibia; S. Afr.: South Africa; SWZ: Eswatini; ZMB: Zambia; ZWE: Zimbabwe Source: authors' computations using results from IMPACT 3.2.

In addition, some countries should diversify away from maize as a staple food to enhance food security under drought. In countries such as Lesotho, Malawi, Mozambique, South Africa, Eswatini, Zambia, and Zimbabwe, maize provides at least 20% of daily caloric intake. In these countries, measures should be undertaken to promote the consumption of drought-tolerant crops such as cowpea and cassava. In Angola where cassava dominates consumption and maize contributes to 14% of daily caloric intake, the recurrent drought of 2014/15 and 2015/16 did not significantly affect food security (Southern African Development Community, 2016). Various studies have also shown the potential for drought-tolerant secondary crops to enhance food security in southern Africa. For example, cassava was identified as a food commodity which could enhance food security in Zambia during drought years (Dorosh et al., 2009). The crop was also found to have the ability to substantially

TABLE 6 Reported versus simulated effect of drought on crop production and food security in southern Africa (%).

	Drought year	Maize (%)	Rice (%)	Traded soy (%)		Traded grdnut (%)		Pigeon p. (%)	Bean (%)		Cowpea (%)		Cassava (%)		Cotton (%)		Tobacco (%)
Angola	2026	−69.6	10.2			−37.4			−69.5				−25.6		45.1	*	
Botswana	2026	−69.5				−2.8											
Lesotho	2026	−42.3							−61.0								
Madagascar	2027	−2.5	−2.8	−29.5	*	2.7			−13.8		1.2		2.8		−31.2		
Malawi	2026	−51.0	−34.9	−28.6		3.5		−4.8	42.3		25.1	*	−10.8	*	16.1		1.8
Mozambique	2027	−46.1	−80.8			−6.5	*						−32.3		19.9	*	
Namibia	2032	−49.4				−16.5			487.2	*					1.4		
South Africa	2040	−44.7	−2.9	−22.8		−20.4			−26.6		19.9				9.6	*	
Eswatini	2030	−33.2				−13.5			−54.9		18.7				−90.3	*	
Zambia	2031	−35.9	1.2	−12.0		3.0							11.4		4.7		−51.4
Zimbabwe	2027	−61.8		−22.8	*	−38.7			76.5	*			19.4		−36.5		−53.6

	Reported increase in food insecure people in 2015/16 vs. 2014/15 (%)	Reported increase in food insecure people in 2016/17 vs. 2014/15 (%)	Simulated increase in people at risk of hunger – first drought (%)	Simulated increase in people at risk of hunger – second consecutive drought (%)
Angola	66	0	1	1
Botswana	3	96	0	0
Lesotho	4	58	39	57
Madagascar	NA	NA	5	NA
Malawi	116	395	7	10
Mozambique	151	1220	19	23
Namibia	392	520	16	31
South Africa*	2	2	59	NA
Eswatini	44	186	10	19
Zambia	127	178	8	12
Zimbabwe	401	621	16	30

Source: For yield difference, authors' computations using results from IMPACT 3.2 and FAOSTAT data; "*": difference between simulated value in Table 4 and reported value on production change in Table 3 is more than 20%; Grdnut = groundnut; pigeon p. = pigeon pea.
For food security, authors' computations using data from Southern African Development Community (2016), and results from IMPACT 3.2; for simulated results, first drought year is 2025 for Botswana and South Africa, 2026 for Angola and Lesotho, 2027 for Madagascar and Zimbabwe, 2030 for Mozambique, 2031 for Zambia, 2032 for Eswatini, and 2036 for Malawi; "NA": no value available; "*": Reported values in Southern African Development Community (2016) are preliminary.

enhance food security in Madagascar during the lean months when rice, the staple food, becomes scarce (Dostie et al., 2002). In Mozambique, cassava consumption varies across urban and rural landscapes. Rural households tend to use cassava to enhance food security during lean months; however, urban consumers, who are less poor, tend to prefer cereals to roots and tubers (Handa and Mlay, 2006). In Malawi, cassava products were shown to have enhanced food security for Malawian households exposed to cassava-based food from some projects in the 1990s (Rusike et al., 2010); in addition, Mango et al. (2018) find that higher crop diversification for selected famers in 4 districts in central Malawi was associated with enhanced food security for rural farm households (Mango et al., 2018). They recommended that the government in Malawi intensifies its policy drive on crop diversification within the country.

Some of the measures which could be used to enhance crop diversification are related to strategic food reserves which are operated in few countries: Malawi, Zambia, and Zimbabwe (Grain Marketing Board (Zimbabwe), 2021; Food Reserve Agency (Zambia), 2022; National Food Reserve Agency (Malawi), 2022). Every year, at harvest time, governments in these countries purchase food produce (mainly maize) from farmers within the country. Policies on strategic food reserves could be adjusted to increase the share of drought-tolerant crops such as dried cassava chips and cowpea purchased annually by governments. In addition, government policy measures in southern Africa could be implemented to ensure that public organizations and parastatals, such as prisons, hospitals, and schools which provide daily meals to a multitude, increase the proportion of drought-tolerant crops in human diets. For rural areas, targeted interventions with awareness campaigns could be conducted to ensure long-lasting adoption of crop diversification by smallholder farmers (Low et al., 2007).

Given that mean annual rainfall is projected to decrease with an increase in heavy precipitation events during the rainy season, it would be imperative for countries in southern Africa to invest in rainwater harvesting techniques that can substantially improve food security during drought years. Indeed, more than 50% of the rainwater which falls across rainfed agricultural systems of sub-Saharan Africa is lost through evaporation, percolation or runoff (Biazin et al., 2012). In addition, enhanced rainwater management alone could double crop yields whereas integrated water and soil fertility management could triple yields across the dryland regions of sub-Saharan Africa (Rockström et al., 2002; Dile et al., 2013). Rainwater can be harvested through ex and *in situ* systems. The *ex situ* systems involve collection of rainwater through macro-catchment systems, whereas the *in situ* systems include micro-catchment rainwater harvesting and techniques to increase water infiltration and reduce soil evaporation (Biazin et al., 2012; Dile et al., 2013). In southern Africa, rainwater harvesting for agriculture occurs at a very small scale. Recent statistics show that only 1.7% of agricultural land receives any form of irrigation in South Africa; in Botswana, the proportion is still less than 0.5%.[3] In Botswana and Zimbabwe, rainwater macro-catchment systems are used and both countries use earthen water dams; Botswana also uses cisterns (Biazin et al., 2012). Micro-catchment rainwater systems are used in Zimbabwe and South Africa; the two countries use pitting and South Africa also uses contouring (Biazin et al., 2012). Capturing rainwater to enhance water and crop productivity across southern Africa would increase food production and enhance community resilience during drought years. Indeed, *ex situ* rainwater harvesting techniques could be used to store water and avail it for food production in drought years. In addition, *in situ* rainwater harvesting techniques could be used in combination with soil fertility techniques to enhance food production during drought years. Hindrances to the adoption of rainwater harvesting techniques among African farming communities, including those in southern Africa, include high investment costs, high labour requirement, high complexity of techniques and inappropriate fit of the techniques with local practices (Mutekwa and Kusangaya, 2006; Backeberg et al., 2009; Biazin et al., 2012). As such, feasibility studies need to be conducted for targeted regions in southern Africa to ensure the promotion of tailored and well adapted rainwater harvesting techniques.

3 Data from World Bank, 2018

6 Conclusion

This study uses an integrated system modeling to quantify the bio-economic impact of future droughts in southern Africa. Results suggest that under moderate economic growth and no drought, food security in southern Africa would only slightly improve by 2040 and the region would not be able to produce or import enough food to substantially mitigate food insecurity. In this context, simulated future droughts would lead to much more erratic agricultural production in the region. Maize, the key staple food, would experience the largest reduction in production under drought when compared to other food and cash crops. Hence, drought would worsen regional food security. Countries which would experience the highest increase in the number of people at risk of hunger due to droughts would be Lesotho, Malawi, Mozambique, Namibia, Eswatini, South Africa, Zimbabwe, and Zambia. Sensitivity analysis on drought frequency suggests that consecutive two-year regional droughts similar to what happened between 2014 and 2015 would substantially affect maize production compared to other crops. Here, maize production would decrease by more than 50% in the consecutive drought year and most countries would experience an increase of at least 10% in the number of people at risk of hunger within a single year. Enhancing regional food security under drought would call for an integrated approach that includes breeding improved maize varieties with enhanced tolerance to the abiotic stresses brought about by drought; diversifying the diet to incorporate more drought-tolerant food crops such as cassava and cowpea; and investing in rainwater harvesting technologies.

Data availability statement

Publicly available datasets were analyzed in this study, as shown in the citations (FAOSTAT, SADC, etc.). The data for the IMPACT model can be found in GitHub (https://github.com/IFPRI/IMPACT/tree/master/DriverAssumptions); in addition, the model code for IMPACT can be found in Robinson et al. (2015) which is also cited in the paper.

Author contributions

DC and SG: initial conceptualization. DC, AA, and SG: contribution to conceptualization and research design. SG: writing manuscript. DC, AA, SK-B, and GC: editing manuscript. 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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Quantifying effects of climate change and farmers' information demand on wheat yield in India: a deep learning approach with regional clustering

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Introduction: With increasing demand for food and changing environmental conditions, a better understanding of the factors impacting wheat yield is essential for ensuring food security and sustainable agriculture. By analyzing the effect of multiple factors on wheat yield, the presented research provides novel insights into the potential impacts of climate change on wheat production in India. In the present study, datasets consisting of countrywide environmental and agronomic factors and wheat yield were collected. In addition, the study also analyzes the effect of information demand of farmers on production.

Methodology: The study employs a regional analysis approach by dividing the country into five zonal clusters: Northern Hills, Central India, Indo-Gangetic Plains, North-Eastern India, and Peninsular India. Correlation and Principal Component Analysis (PCA) were performed to uncover the month-wise key factors affecting wheat yield in each zone. Furthermore, four Machine Learning/Deep Learning-based models, including XGBoost, Multi-layer Perceptron (MLP), Gated Recurrent Unit (GRU), and 1-D Convolutional Neural Network (CNN), were developed to estimate wheat yield. This study estimated partial derivatives for all factors using Newton's Quotient Technique, a numerical method-based approach.

Results: The analysis focused on applying this technique to the best-performing wheat yield estimation model, which was the GRU-based model (with RMSE and MAE of 0.60 t/ha and 0.46 t/ha, respectively).

Discussion: In the later sections of the article, multiple policy recommendations are communicated based on the extracted insights. The results of the presented research help inform decision-making regarding the development of strategies and policies to mitigate the impacts of climate change on wheat production in India.

KEYWORDS

agricultural modeling, AI in agriculture, deep learning, environmental factors, helpline data, wheat yield

1 Introduction

Wheat, a vital crop globally, ensures food security for millions. India, ranking second in wheat production after China (Shukla et al., 2022), contributes ≈8% of the world's annual production, yielding around 105 million tonnes. Over the years, the wheat cultivation area in India has expanded, covering more than 30 million hectares (Ramadas et al., 2019). For farmers, particularly in northern and central regions, wheat serves as a crucial source of income.

In this scenario, the Indian government has implemented various policies and programs to promote wheat cultivation and increase production, such as the National Food Security Mission and the Pradhan Mantri Fasal Bima Yojana (Chopra, 2022). However, the crop is also affected by various environmental and agronomic factors, which can impact yield. Understanding these factors is essential for improving crop productivity and addressing food insecurity in India. In this context, the presented study aims to identify the factors affecting wheat yield in India and analyze their impact on production using Machine Learning/Deep Learning (ML/DL)-based models.

The existing studies have found that changes in average minimum and maximum temperatures can directly impact wheat yield (Asseng et al., 2011). This highlights the vulnerability of agricultural systems to changes in temperature patterns and the need to adapt to such changes to ensure food security. Secondly, changes in rainfall patterns also impact wheat yield (Birthal et al., 2021). Of all the factors at play, rainfall and temperature are deemed the most pivotal variables affecting wheat yield, owing to their direct impact on crop growth and development (Birthal et al., 2021). Adequate rainfall ensures sufficient water availability for plant growth, while optimal temperature ranges promote optimal physiological processes. Considering these factors allows for an accurate wheat yield estimation, which is crucial in determining crop productivity. However, understanding the factors affecting wheat yield is a complex task. The complexity of the crop's biology and the dynamic interactions between various factors make it challenging to identify the most critical factors affecting yield (He et al., 2022). Additionally, various regions in India with different climates, soil types and farming practices make the analysis of factors affecting yield more complex (Bhardwaj et al., 2022).

The concept of crop yield estimation utilizing remote sensing data was first introduced in the late 1970's, with MacDonald and Hall (1980) pioneering the estimation of harvests in strategically significant counties. Moreover, process-oriented crop simulation models, such as DSSAT, APSIM, WOFOST, MCWLA, and AQUACROP, can provide improved crop yield estimation when combined with remote sensing data (Lobell, 2013; Sakamoto et al., 2013; Huang et al., 2015; Lobell et al., 2015). These models can adapt to changes in location, weather conditions, and timing of images to produce yield estimates for each pixel. However, these models often require more in-depth input data, including site-specific soil and daily weather information. This, coupled with the computational costs, can make it challenging to scale the approach to cover multiple crops, regions, and years without incurring significant time, monetary, and labor investments.

On the other hand, traditional statistical-based methods, using specific response functions between yields and independent variables, offer a simpler and more effective alternative for yield predictions. (Huang et al., 2015; Qader et al., 2018). However, these empirical regression models are often limited in spatial generalization and suffer from local specificity (Folberth et al., 2019). To overcome these limitations, it is essential to develop innovative approaches for accurate, timely, and low-cost yield estimation over large areas.

In recent years, in many countries, ML techniques have been widely adopted in agriculture research, including crop classification, growth monitoring, and yield prediction (Shah et al., 2019; Wolanin et al., 2019). ML is a subset of artificial intelligence where algorithms learn patterns and make predictions from data without explicit programming. DL is a type of ML that uses neural networks with multiple layers to learn hierarchical representations of data, enabling complex feature learning and abstraction. Unlike traditional ML algorithms, DL methods automatically extract features from raw data, eliminating the need for manual feature engineering. Due to their complex nature, DL architectures require large amounts of data and computational power to train effectively. While both ML and DL aim to extract insights from data, DL excels at handling unstructured data like images, audio, and text, often achieving state-of-the-art performance in various tasks. ML approaches, such as regression tree, support vector machine (SVM), random forest (RF), and neural network (NN), have been shown to perform better than traditional regression methods in yield prediction studies (Cai et al., 2019).

Furthermore, DL has emerged as a powerful tool in yield estimation, with its ability to transform raw input data into high-level abstract representations through multiple non-linear layers (Kuwata and Shibasaki, 2015; Khaki and Wang, 2019). For example, You et al. (2017) used Convolutional Neural Network (CNN) and Long Short-Term Memory (LSTM) to estimate soybean yields in the US and achieved better results compared to traditional statistical-based methods and USDA estimations. Cao et al. (2021) designed a Deep Neural Network (DNN) with 21 hidden layers and 50 neurons in each layer to predict maize yield in 2017 and achieved superior accuracy compared to LASSO, shallow neural networks (SNNs), and regression trees (RTs).

Barbier et al. (2015) explores the intersection of Computer Science and Agronomy, highlighting the potential of Model-Driven Engineering as the future of software engineering for crop modeling and simulation. The proposed metamodel and graphical syntax address the need for formal tools in conceptual modeling, leading to improved production processes and industrial application in the ITK Company. Gupta et al. (2022) provides a comprehensive review of modeling technologies in climate-smart agriculture (CSA), emphasizing advancements in crop simulation models, hydrological models, and the potential of AI-based approaches. It highlights the importance of these models for improving crop and environment estimation, field management, and decision-making in CSA. Furthermore, the study by Jamali et al. (2023) developed a methodology using vegetation indices (VIs) from sentinel-2 data and machine learning algorithms to estimate leaf parameters in wheat. The results showed that the DNN model achieved high precision in predicting leaf parameters, demonstrating the potential for accurate crop monitoring and management.

A study by Santos et al. (2023) aimed to propose a methodology utilizing Lautilizinga for predicting and projecting eucalyptus forest growth and yield and analyzing dynamics. Different scenarios with varying sample sizes were assessed to evaluate potential cost savings. Artificial neural network (ANN) and random forest (RF) algorithms were employed for estimation, resulting in relative root mean square error (RRMSE) values ranging from 7.9 to 14.5% for wall-to-wall prediction and 6.8–11.8% for projection. Seyedmohammadi et al. (2023) aimed to predict yield and effectively manage natural resources in the study by modeling the impact of soil properties using various algorithms such as classification and regression tree, k-nearest neighbors, support vector machines, and a hybrid model combining support vector machines with the firefly meta-heuristic algorithm. Soil samples from 124 pistachio orchards in Iran were analyzed, and critical predictors were selected based on correlation coefficients, sensitivity analysis, and ANOVA hypothesis testing. The hybrid model outperformed other algorithms, explaining 94% of the variation in pistachio yield by efficiently capturing non-linear relationships. The research by Son et al. (2022) demonstrates the potential of using ML techniques and monthly image composites from Sentinel-2 satellite imagery to predict rice crop yield in Taiwan. Three ML models (random forest, support vector machine, and artificial neural networks) were employed, with the support vector machine performing slightly better. The validation results showed close agreement between the predicted yields and government statistics, with low root mean square percentage error and mean absolute percentage error values.

Research by Pagano et al. (2023) explores the use of Artificial Intelligence models, specifically Multi-Layer Perceptron (MLP) and Random Forest (RF), to predict daily actual evapotranspiration in a Mediterranean citrus orchard. It demonstrates that these models, especially Random Forest with seven input features, can achieve accurate predictions, leading to significant water savings of up to 38.5% compared to full irrigation. Incorporating soil water content, weather, and satellite data enhances the accuracy of evapotranspiration forecasts compared to models using only meteorological variables. Another work by Singh et al. (2023) used thermal and visible imaging along with machine learning techniques to estimate plant disease severity under field conditions, overcoming the limitations of existing methods. The study found that combining machine learning models using model combination techniques significantly improved the accuracy of disease severity prediction in chickpea crops with wilt resistance. A study by Prasad et al. (2023) used earth observation data and an ensemble model, combining random forest (RF), support vector machine (SVM), and multivariate adaptive regression spline (MARS) models, to create a highly accurate wetland map. The ensemble model achieved an impressive 96% accuracy when cross-validated with field data and demonstrated the effectiveness of integrating multiple key variables for probabilistic wetland mapping, providing valuable insights for coastal area planning and sustainable development.

Lv et al. (2013) analyzed the spatial pattern of wheat yield using cluster analysis and emphasized the need to address the spatial gap and improve production over time. To identify the factors affecting wheat production, techniques such as the spatial Durbin model (Zhang and Li, 2022), stepwise regression analysis (Zhang et al., 2021), farmer field surveys (Zhang and Li, 2022), and machine learning (Yu et al., 2022) are utilized. The consensus is that the impact of crop yield is multidimensional, and climate factors have the most direct effect on regional differences in yield (Fen et al., 2020; Lin and Shao, 2020; Twizerimana et al., 2020).

The existing studies demonstrate the potential of using machine learning and deep learning techniques to predict wheat yield and identify the most critical factors affecting yield. These models can analyze large and complex datasets and identify patterns and relationships that may not be apparent from traditional statistical methods. However, it is essential to note that these models must be trained on a large and diverse dataset to achieve accurate predictions. Despite the advancements in this field, there are still some limitations to the existing research on the factors affecting wheat yield in India, which have been addressed in the present study.

- One limitation is that many studies have focused on specific regions or states rather than the entire country. Generalizing the findings to other regions or the entire country is difficult. Additionally, many studies have used observational data, which can limit the quality and completeness of the data. Observation data may not represent the entire population or cover all the relevant factors affecting wheat yield.
- Most studies focus on single data points for environmental factors, such as cumulative rainfall and average temperature for the entire season. Still, a comprehensive understanding of these factors requires considering them month- or stage-wise.
- Another limitation is that most studies have used machine learning and deep learning models for prediction. However, interpreting and understanding these models are complex, and it is not always clear how the model arrived at its predictions. This can make it challenging to understand the underlying factors affecting wheat yield. Therefore, further analysis is needed, such as extracting the factor-wise partial derivatives using the trained models.
- Additionally, many studies have evaluated the performance of these models only on the training datasets, which can lead to overfitting of the model. Overfitting occurs when a model is too complex and fits the training data too well but needs to perform better on new data. This can lead to inaccurate predictions and unreliable conclusions. Therefore, in the presented study, the models are assessed based on their performances on unseen (testing) data.

In the present study, the environmental factors are analyzed monthly for the rabi season, i.e., the rainfall and temperature parameters are analyzed separately for October to April. This helps to gain novel insights regarding the month-wise effects of the considered factors. In addition, the study analyzes the correlation between wheat yield and various environmental factors and factors related to farmers' demand for information. For this objective, data corresponding to the farmers' demand for assistance regarding various topics were also collected from the nationwide farmers' helpline network, i.e., Kisan Call Centers (KCC; Godara and Toshniwal, 2022). Moreover, the study uses ML/DL-based models to predict wheat yield based on the considered factors. The study also investigates the scale of impact each factor has on the yield using the numerical method-based partial derivatives. Overall, the presented study is aimed to answer the following research questions:

- What are the most critical (month-wise) factors affecting wheat yield in India?
- How do these (environmental, agronomic, etc.) factors impact wheat yield concerning different climatic zones?

Moreover, the analysis of the KCC data provides insights into the information needs of farmers and how they seek information to improve their crop yields. The results of this analysis can help policymakers design effective extension delivery systems to meet the needs of farmers, particularly concerning their information needs. This can be essential to improving agricultural productivity and supporting sustainable farming practices in the face of changing climate conditions. The research work presented in this study offers several novel contributions. Firstly, it investigates the specific effects of month-wise environmental factors, such as rainfall and temperature, on wheat yield, providing valuable insights into the impact of these variables. Additionally, it explores the influence of farmers' demand for information on yield, shedding light on the relationship between farmers' needs and crop productivity. The development of a DL-based model incorporating both environmental factors and farmers' assistance data is another innovative aspect (a total of 36 variables considered), enabling more accurate wheat yield prediction. Lastly, introducing LDI-based merging of nationwide district-wise datasets enhances the comprehensive analysis by integrating diverse information sources.

The initial step involved collecting data about diverse environmental factors, such as rainfall and temperature, to accomplish the set objectives. This data was acquired in a 1x1 grid format based on latitude and longitude coordinates and converted into a district-wise representation. In addition, information regarding the irrigated area corresponding to each district was considered in the study. A major challenge in merging various datasets is that the district and state names do not exactly match when collected from different sources. And the manual matching of thousands of records is an infeasible task. We have introduced a Levenshtein Distance Index (LDI) for merging (agricultural district-wise) datasets to tackle this problem. Later, data corresponding to district-wise wheat yield and farmers' demand for assistance from all over India were merged. To have a more practical analysis, the whole dataset is clustered into five groups according to their climatological properties, i.e. Northern Hills, Indo-Gangetic Plain, Central India, Peninsular India and North-Eastern India.

In the next step, a correlation analysis was done to identify the association between wheat yield and various factors (each month, corresponding to each cluster, separately). Further, PCA was done to identify the factors explaining the most variance in the dataset. Subsequently, four ML/DL-based models (XGBoost, Multi-layer Perceptron (MLP), Gated Recurrent Unit (GRU), and 1-D Convolutional Neural Network (CNN)) were trained to predict wheat yield based on the collected data, and the best-performing model was chosen for further analysis. The ML/DL models offer several advantages for agricultural applications. Firstly, these models can effectively capture complex relationships between input variables (such as environmental factors) and crop yield, enabling accurate predictions. Secondly, ML/DL models can handle large volumes of data and automatically learn patterns, reducing the need for manual feature engineering. Finally, the working of these models involves training the model on historical data to learn the underlying patterns and then using the trained model to make predictions on new, unseen data, allowing for continuous improvement and adaptation to changing conditions.

Lastly, the partial derivatives (PD) corresponding to each factor are calculated in the study and analyzed to capture an exhaustive understanding of each undertaken factor. A significant challenge in calculating PD with a DL-based model is that it is inconvenient to calculate the PD through mathematical derivation. The challenge in calculating PD with a DL-based model arises due to deep learning architectures' complex and nonlinear nature. These models have multiple layers and thousands of parameters, making it challenging to derive the PD concerning each input variable analytically. The intricate interactions and transformations within the model make obtaining explicit mathematical equations for the derivatives difficult. Therefore, in the presented study, a numerical method-based approach was used. The following are the major research contributions of the presented study:

- Analysis of the effects of month-wise environmental factors (rainfall and temperature) along with the topic-wise farmers' demand for information on wheat yield.
- Deep learning-based model development for wheat yield prediction using environmental factors and information regarding farmers' demand for assistance (total 39 variables considered).
- Introduced LDI-based merging of nationwide district-wise datasets (environmental, yield, and farmers' helpline data).
- Introduced partial derivative-based factor analysis using the DL-based model to understand factors' effect on wheat yield.

The remainder of the paper is organized as follows: Section 2 elaborates on the related research works. The details of the proposed methodology used in the study are presented in Section 3. Section 4 gives the results obtained through the proposed methodology. A discussion of the obtained results and recommended policies is given in Section 5. Section 6 gives a summary of the presented work.

2 Methodology

2.1 Data collection and preprocessing

The data collection and preprocessing process is illustrated in Figure 1. The data for the study was collected from various sources, such as daily grid-wise rainfall data and daily grid-wise minimum and maximum temperature data from the India Meteorological

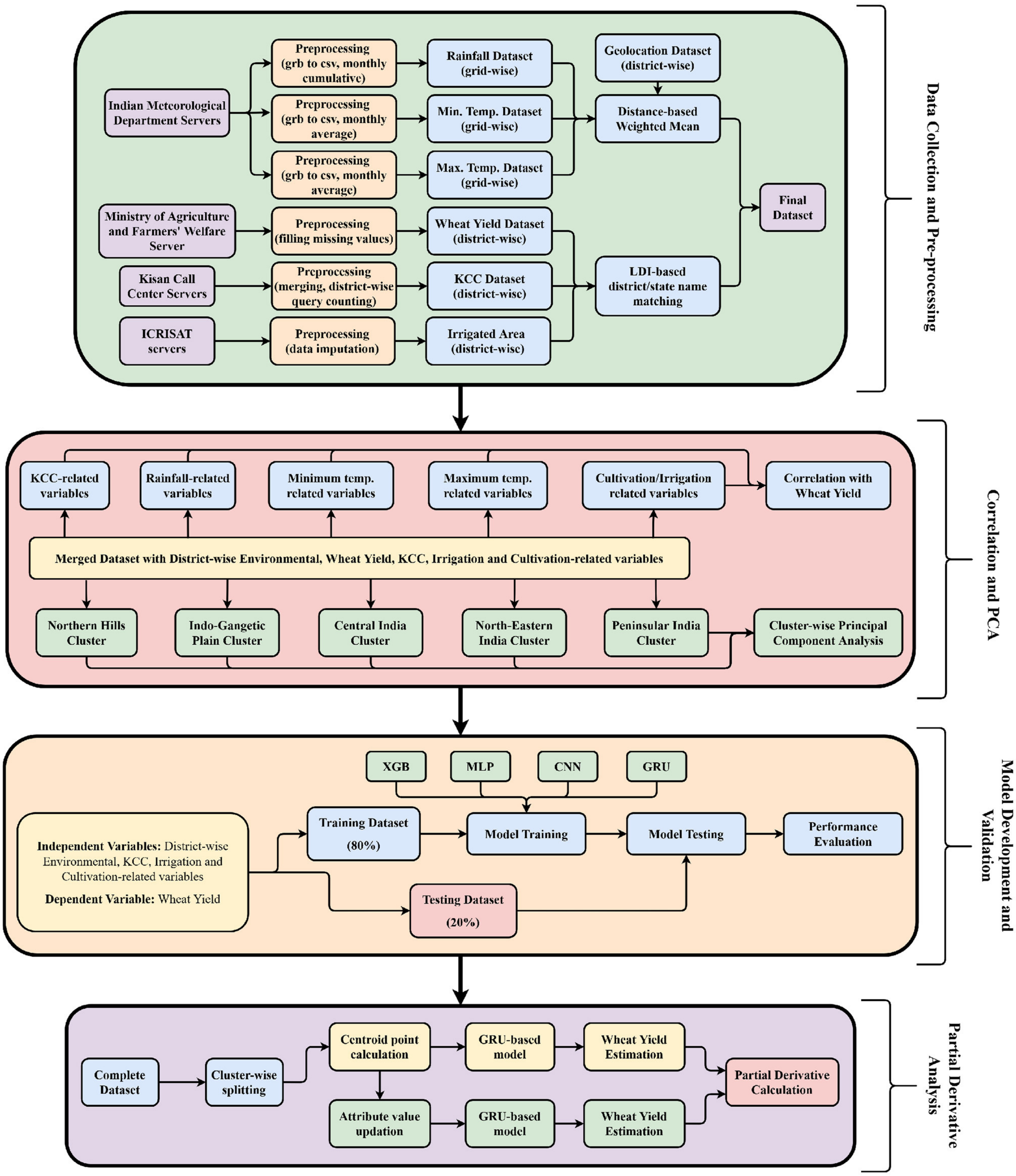

FIGURE 1
Approach used in the study to analyze factors influencing wheat yield.

Department (IMD) servers (MOES, 2023), *https://mausam.imd.gov.in/* for the years 2009–2020, Kisan Call Center data from the Kisan Knowledge Management System (DAFW, 2020), area of cultivation and wheat yield data (DAFW, 2023) at the district level from the Ministry of Agriculture and Farmers' Welfare of India, and data on the area of irrigated land at the district level from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) servers (ICRISAT, 2023).

It is important to note that the data preprocessing step is crucial for ensuring the accuracy and reliability of the results in the study. The preprocessing step involves cleaning, transforming, and organizing the data in an easily analyzed format. This step helps to remove errors, inconsistencies, and outliers from the data and prepares it for further analysis. Once the data was collected, it underwent a series of preprocessing steps. The first step involved converting the grid data into district-wise data and merging all the data using the proposed Levenshtein Distance index. This merging process was necessary since the available yield data was in district rather than grid format. The distance-based weighted average (Equation 1) was used for the grid-to-district conversion of the rainfall, minimum and maximum temperature data.

$$s = \frac{\sum_{i=1}^{p} (D_i \times a_i)}{\sum_{j=1}^{p} D_j}$$
$$where,\ D_i = \sqrt{(lat_i - lat_d)^2 + (lon_i - lon_d)^2} \quad (1)$$

Here, a_i represents the (rainfall/temperature) data of the i^{th} closest grid point concerning the latitude (lat_d) and longitude (lon_d) of the district record being processed, and lat_i and lon_i are the latitude and longitude of the i^{th} closest grid point to the target district. p represents the number of grid points for calculating the target district's average (environmental factor) value.

Moreover, the datasets corresponding to the rainfall and (min. and max.) temperature are available daily. The rainfall data were cumulated for October to April (rabi season) from 2009 to 2020. In addition, the temperature data was month-wise averaged for the same period.

Another challenge researchers face while merging the district-wise datasets is the spelling of the district names in the various dataset mismatches. Moreover, this is the only attribute that can be used for merging the datasets. Nevertheless, manual matching of the nationwide multiple datasets is a challenging task. To overcome this challenge, we developed a Levenstien Distance Index, which indicates the edit distance of two words by comparing their length. The well-known Levenstien Distance or edit distance (Mullin, 1985) is a widely used metric to perform this task, but the metric doesn't inform anything related to the lengths of the words being compared. To overcome this problem, we present a modified version of the same (Equation 2).

$$ldi(n_1, n_2) = \left(1 - \frac{ld(n_1, n_2)}{max(|n_1|, |n_2|)}\right) \times 100$$
$$where,\ ld(x,y) = \begin{cases} |x| & \text{if } |x| = 0, \\ |y| & \text{if } |y| = 0, \\ ld(tail(x), tail(y)) & \text{if } if\,|x| = |y|, \\ 1 + min \begin{cases} ld(tail(x), y) \\ ld(x, tail(y)) \\ ld(tail(x), tail(y)) \end{cases} & \text{otherwise} \end{cases} \quad (2)$$

Here, n_1, n_2 are the input character strings between whom the LDI is to be calculated, $|n_1|$ represents the length of string n_1, and $tail(x)$ is the string x without the first character. The LDI ranges from 0 to 100%, indicating the match percentage found between the input strings.

To merge the district-wise records of two datasets, first, the LDI is calculated for each record from the primary dataset with every record of the secondary dataset (district names from each dataset being matched). If the minimum LDI corresponding to a target record is found to be more than 70%, then the records are merged; otherwise, the record is discarded.

The data regarding the variables corresponding to the farmers' demand for information is captured from the Nationwide Farmers' Helpline Network (Kisan Call Centers (KCC; DAFW, 2020), run by the Government of India as a free service to the Indian farmers since 2004. The KCC services provide telephonic help to Indian farmers on all agriculture-related topics. Furthermore, the Ministry of Agriculture and Farmers' Welfare keeps call-log records (in text format) of each query call made by the farmers. It has made the data publically available on the open data platform (NIC, 2023). The KCC dataset contains individual query-call logs, with each row representing a distinct log entry. The dataset encompasses multiple attributes, including the farmer's question, the corresponding response, crop information, query type, category, time, location, and more. Comprehensive details about these attributes can be found in Godara and Toshniwal (2020).

In the presented study, 14 variables related to KCC are taken into account, representing the 14 most popular topics that farmers have been asking for the past 11 years (2009–2020) regarding the wheat crop (Supplementary Table 2) Moreover, each variable represents the district-wise number of query calls related to the particular topic per hectare (cultivation area).

2.2 Correlation and PCA analysis

The data splitting process and performing correlation and PC analysis is illustrated in Figure 1. The (merged) input dataset for this phase contains five types of variables in it, i.e., district-wise KCC (14 variables), Rainfall (seven variables), Temperature (Min. temp. + Max. temp. = 7 + 7 = 14 variables), and two variables regarding the Area of Cultivation and Irrigated Area. In addition, a derived variable is also considered as an interaction of the Irrigated Area × Max. Temperature.

The correlation analysis helps understand the relationship between each independent variable and the dependent variable of wheat yield (Equation 3). It helps identify the variables that strongly or negatively impact the wheat yield.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (3)$$

Here, x_i represents the values of the x-variable, $\bar{x}$ represents the mean of the values of the x-variable, y_i is the values of the y-variable in a sample and $\bar{y}$ represents the mean of the values of the y-variable. In the presented study, the correlation analysis of each variable is performed separately. Furthermore, to understand the variables in terms of linear relation with the wheat yield, the data points are further divided into five clusters (based on different climatological zones) for the analysis.

The PCA transforms the independent variables into a new set of uncorrelated variables called the principal components

(Abdi and Williams, 2010). PCA is a popular method for dimensionality reduction in data analysis. A linear technique transforms the original data into a lower-dimensional representation through a linear projection. The main goal of PCA is to reduce the number of dimensions while exploring the relationships between variables. It is commonly used as a preprocessing step before applying other statistical methods, such as regression or clustering. By transforming the data into orthogonal principal components, PCA ensures independence between variables and enhances the accuracy of regression and clustering methods.

Generally, the first principal component (PC1) explains the maximum variance in the data, and the subsequent PCs explain the remaining variance. Calculating the PCA for different zones of India separately helps understand the regional variability in the impact of different variables on wheat yield. Moreover, in the presented study, PCA is performed to capture the variables that show the highest variance in the dataset. In addition, the variable that captures similar data point variance is also obtained from the analysis. For the PCA, the whole dataset is divided into five clusters, and PCA is performed on each cluster separately (Figure 1).

2.3 Model development and validation

In the Model Development and Validation phase, four ML/DL-based models (XBG, MLP, CNN, and GRU) are trained and tested to predict the district-wise wheat yield based on the environmental, KCC and other variables. Brief information regarding the working of each of the considered models in the study is as follows:

1. XGBoost (XGB): is a highly effective machine learning algorithm that belongs to the Gradient Boosting Trees (GBT) model class. It was developed to optimize the performance and scalability of GBT models by Chen and Guestrin (2015). XGBoost stands for eXtreme Gradient Boosting, and its popularity can be attributed to its remarkable performance in real-world applications.

   The XGBoost model uses a decision tree-based approach for regression and classification tasks. It is an optimized implementation of gradient boosting that uses parallel computing and advanced memory management techniques. In XGBoost, the trees are built sequentially, where each tree is built to correct the errors made by the previous tree. This allows XGBoost to handle non-linear relationships between independent variables and the dependent variable. The algorithm also uses a penalty term to control overfitting, and the penalty term can be tuned using cross-validation techniques. The XGBoost algorithm is a gradient boosting method incorporating a regularization term into the objective function (Equation 4) to mitigate overfitting.

$$Obj^{(r)} = \sum_{i=1}^{n} L(y_i, \hat{y}_i^{(r)}) + \sum_{i=1}^{r} \Omega(g_r) \tag{4}$$

   Where y_i is the actual value, $\hat{y}_i^{(r)}$ is the prediction of the r^{th} round, g_r denotes the structure of the decision tree, $L(y_i, \hat{y}_i^{(r)})$ represents the loss function, n is the number of training examples, and $\Omega(g_r)$ is the regularization term, derived from the number and weights of the leaf nodes.

2. Multi-Layer Perceptron (MLP): is a type of artificial neural network that is widely used for supervised learning problems (Kruse et al., 2022). It is a feedforward network with multiple hidden layers of artificial neurons that use non-linear activation functions to model complex relationships between inputs and outputs. The working of a neuron can be mathematically described by Equation (5).

$$y_j = \psi\left(\sum_{i=1}^{u} w_{ji} x_i\right) \tag{5}$$

   Where ψ is the activation function utilizing the weighted summations of the inputs, and u represents the number of nodes in the previous layer. The model is trained using the backpropagation algorithm, which calculates the error between the predicted output and the actual target and adjusts the network weights accordingly. MLP is highly flexible, capable of modeling a wide range of problems, and has been shown to produce good results in many real-world applications. The model is beneficial when the relationship between inputs and outputs is highly non-linear and cannot be modeled effectively by traditional linear regression techniques.

3. 1-D Convolutional Neural Network (CNN): is a deep learning architecture designed for processing sequences of data, such as time series, signals, or sequences of words. In contrast to traditional 2-D CNNs, designed for image processing, 1-D CNNs operate on sequences by sliding a filter window along the temporal dimension of the input data. The filters in a 1-D CNN learn to extract relevant features from the input sequence, such as patterns, trends, or anomalies. The extracted features are then fed through a series of fully connected layers to produce a prediction. Using convolutional layers in 1-D CNNs allows for the efficient learning of spatial dependencies in the data, as the same filter can be applied at different positions along the sequence.

   The complete dilated causal convolution operation F over consecutive layers for a 1-D sequence of a given input $f \in R^n$ and a filter $f : \{0, ..., k-1\} \to R$, on element s of the sequence, is defined by Equation (6):

$$F(s) = (q *_d f)(s) = \sum_{i=0}^{k-1} f(i).q_{s-d.i} \tag{6}$$

   where, d is the dilation factor, k is the filter size, and $s - d.i$ accounts for the direction of the past.

4. Gated Recurrent Units (GRU): are a type of Recurrent Neural Network (RNN) architecture used for sequential data processing. GRU was introduced as an improvement over traditional RNNs as they are more computationally efficient and can capture long-term dependencies more effectively. In a GRU regression model, the network receives a sequence of inputs and utilizes hidden states to process the information and predict an output value. The model leverages the gating mechanism in GRUs to control the flow of information and decide which information to preserve and discard, resulting in more robust and accurate predictions. The model can be trained using various optimization algorithms such as stochastic gradient descent (SGD) or Adam to minimize the prediction

error and improve its performance. A GRU unit has two gates, i.e., the update gate and the reset gate. The working of the reset gate can be mathematically described by Equation (7).

$$r_t = \sigma(W_r[h_{t-1}, X_t] + b_r) \tag{7}$$

Where r_t, W_r and b_r are the output vector, the weight and the bias of the gate, respectively. Like the reset gate, the update gate determines the updation level to be done in the received data (Equation 8). The output (h_t) of the unit is a linear interpolation between the element-wise multiplication of h_{t-1} and update gate output z_t, and the element-wise multiplication of $\hat{h}$ and $(1 - z_t)$ (Equation 10). Here, $\hat{h}_t$ is calculated using the reset gate output and the current input as shown in Equation (9).

$$z_t = \sigma(W_z[h_{t-1}, X_t] + b_z) \tag{8}$$

$$\hat{h}_t = tanh(W_h[r_t * h_{t-1}, X_t] + b_h) \tag{9}$$

$$h_t = (1 - z_t) * h_{t-1} + z_t * \hat{h}_t \tag{10}$$

Where W_z, W_h, b_z, and b_h are the weights and biases used in the update gate.

First, the dataset is divided into two parts for the development of the regression models: training (80%) and testing (20%). Later, the hyperparameter tuning was performed based on the grid-based search technique (Bergstra et al., 2011) to find the optimal architecture of the models. The study incorporates several hyperparameters for model optimization, encompassing batch size, number of epochs, layer count, layer size, and activation functions for each layer.

Furthermore, the models learn from the historical data using the backpropagation technique, a fundamental algorithm used in neural networks to calculate the gradients of the model's parameters concerning the loss function (Smolensky et al., 1996). It involves the iterative process of propagating the error from the output layer back to the input layer, updating the weights and biases along the way, and enabling the network to learn and adjust its internal representations to improve its predictions. The models were first trained on the training data, and then their performance was evaluated using the Root Mean Squared Error (RMSE, Equation 11) and Mean Absolute Error (MAE, Equation 12) on the testing data.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2} \tag{11}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Y_i - \hat{Y}_i| \tag{12}$$

where, n is the number of output data point, $\hat{Y}$ is the output of the forecasting model, and Y is the desired value. Finally, a Diebold Mariano test was performed between the outputs of each model to determine if the outputs of the models are statistically significantly different (Costantini and Kunst, 2011).

2.4 Partial derivative analysis

The partial derivative analysis involves calculating the derivative of a function concerning one or more independent variables while holding all other variables constant. It provides an estimate of how much the output of a function changes concerning a slight change in one of the inputs. The partial derivative analysis could be used to understand the effect of independent variables such as monthly cumulative rainfall and average min./max. temperature, and calls to the Kisan Call Center about specific topics on the wheat yield. The result of the partial derivative analysis can provide valuable insights into which independent variables impact the wheat yield most and in which direction. This information can be used to make informed decisions about improving the wheat yield and mitigating adverse effects.

Generally, the partial derivative corresponding to each variable is calculated by first obtaining the mathematical representation of the model and later deriving the partial derivative using the obtained function (Birthal et al., 2021). In contrast, representing complex ML/DL-based models using a mathematical function and deriving partial derivatives is infeasible. Therefore, in the presented study, we used a numerical method-based technique named Newton's Quotient to calculate the same (Figure 1). In the proposed technique, the centroid points corresponding to each data cluster are first calculated using Equation (13):

$$C_i = \langle c_1, c_2, ..., c_k \rangle$$
$$where,\ c_j = \frac{1}{n_i}\sum_{m=1}^{n_i} x_{jm} \tag{13}$$

Here, C_i represents the centroid vector for the i^{th} cluster, n_i represents the total number of rows in the i^{th} cluster (climatic zone), and x_{jm} represents the m^{th} row element of the j^{th} column. In the second step, the partial derivative is calculated using Equation (14):

$$\frac{\partial f(C_i)}{\partial v_j} = \frac{f(C_i^j) - f(C_i)}{h^j}$$
$$where,\ C_i^j = \langle c_1, c_2, ..., (c_j + h^j), ..., c_k \rangle$$
$$and,\ h^j = c_j \times 0.001 \tag{14}$$

Here, v_j is the variable corresponding to which the partial derivative is calculated for the zone with C_i as the centroid point. The presented study calculates the partial derivative for each variable corresponding to each cluster (zone) separately.

3 Experiments and results

3.1 Data and descriptive analysis

Figure 2A shows the states corresponding to five zones, which are considered in the presented study for analyzing the factors behind the yield of wheat crops. Here, each zone covers different climatological regions. Supplementary Table 1 gives the data points corresponding to each climatic zone collected and processed in the study. Previous research has demonstrated that deep learning

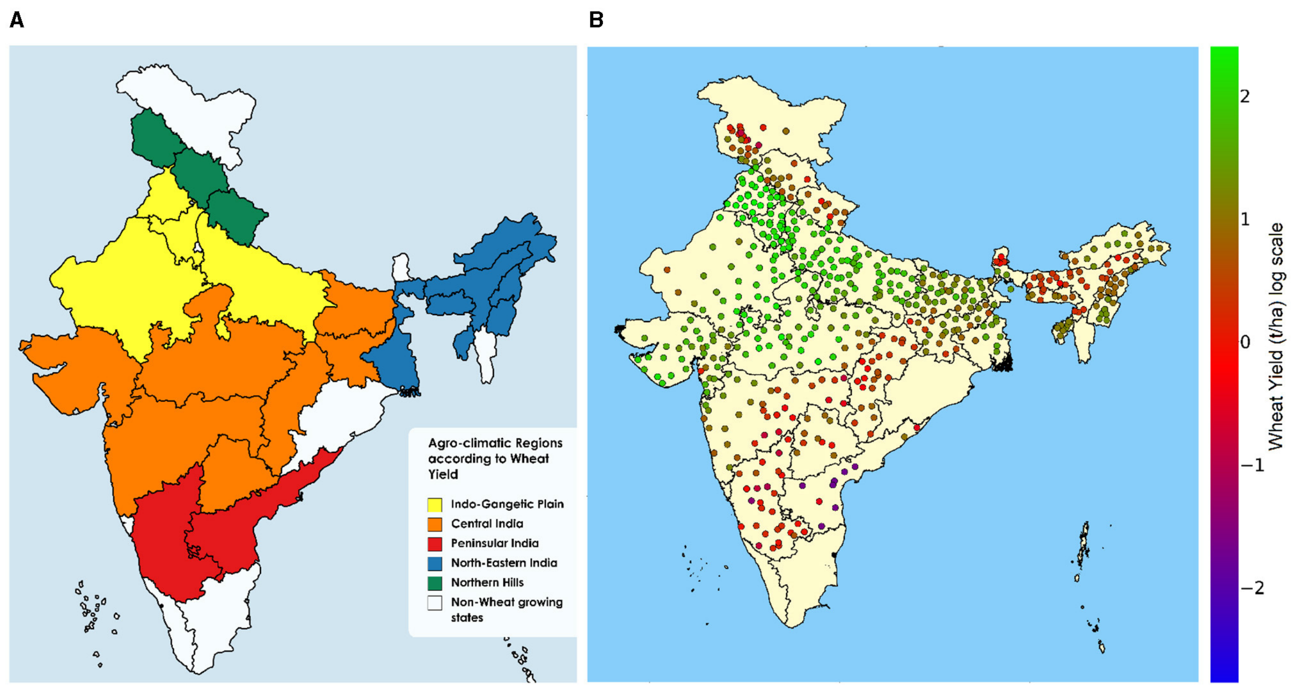

FIGURE 2
(A) India's wheat production categorized by agro-climatic zones, **(B)** district-wise wheat yield (t/ha) in log scale.

models can capture patterns from data points spanning a wide range, typically from 2000 to 10,000 (Barbier et al., 2015; Cai et al., 2019; Birthal et al., 2021). Our study utilized ∼4,500 data points, covering 11 years from 2009 to 2020. Moreover, Figure 2B plots the district-wise wheat yield (in log scale) on the India map. The graph shows that yield is high in Indo-Gangetic and Central India. Whereas in other zones, the yield of wheat is comparatively less.

Similar to the yield map, Supplementary Figure 1A gives the area of wheat cultivation corresponding to each considered district of India. The graph shows that the cultivation area in the districts is high in Indo-Gangetic plains and Central India (more than 25e4 ha per district). In other parts of India, the wheat cultivation area is <10e4 ha per district. In addition, from the map, it can be seen that there are no data points in India's extreme North, extreme South and South-Western coastal region. This is because wheat is not grown in these regions; therefore, districts from these regions are not considered in the present study. Supplementary Figure 1B illustrates the irrigated area in each district (hectares/1e4). From the map, it is noticed that the states Haryana and Punjab are highly irrigated. Moreover, Uttar Pradesh and Madhya Pradesh districts need to be more irrigated. In addition, other zones (Northern Hills, North-Eastern India, and Peninsular India) are the least irrigated regions of India for the wheat crop.

Supplementary Figure 2A plots the daily minimum temperature (captured at 2:00 a.m.) corresponding to the December month from all the considered districts. The graph shows that the northern hills have temperatures $<5.0^{\circ}C$ this month. In addition, the Indo-Gangetic plains, North-eastern and central India, have an average minimum temperature of $7.5\text{-}12.5^{\circ}C$. Whereas, in the Peninsular zone of India, the minimum temperature is noted to be more than $15.0^{\circ}C$. A similar pattern is noted in the graph corresponding to the district-wise average daily maximum temperature (captured at 2:00 p.m., Supplementary Figure 2B). Here, the temperature is shifted to $10^{\circ}C$ more than the minimum temperature. Table 1 gives the mean and standard deviation of the values regarding the (monthly average min. and max.) temperature variables.

Supplementary Figure 3A shows the district-wise rainfall corresponding to the April month of 2019 (in mm, log scale). The study (PCA results) has shown that rainfall corresponding to April captures the most variation of the dataset. The map shows high rainfall in the Northern hills, North-Eastern and Peninsular India. In contrast, the rainfall in the western part of central India (Gujarat state) is noted to be the least in this month. The mean and standard deviation values present in the rainfall-related variables are given in Table 2 zone-wise.

Supplementary Figure 3B plots the KCC query index (Equation 15) corresponding to the weather-related questions (in log scale) asked by the farmers of the respective districts.

$$KCC_{ijk} = \frac{Number\ of\ query\ calls\ corresponding\ to\ i^{th}\ topic\ in\ j^{th}\ year\ for\ the\ k^{th}\ district}{Area\ of\ wheat\ cultivation\ in\ j^{th}\ year\ corresponding\ to\ the\ k^{th}\ district} \quad (15)$$

The graph shows that the farmers from the Indo-Gangetic plain asked many questions related to the other zones. The map shows that there is some common pattern in the regions where farmers ask more questions (regarding weather) with the regions of high wheat yield and area of cultivation per district (Figure 2B). Table 3 gives

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TABLE 1 Description of temperature-related variables in Celsius within the dataset.

Climatic zone	October		November		December		January		February		March		April	
	Min. temp.		Min. temp.		Min. temp.		Min. temp.		Min. temp.		Min. temp.		Min. temp.	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
Central India	15.39	2.32	11.62	2.42	10.71	2.40	13.67	2.20	17.71	2.04	22.50	1.85	25.61	1.91
Indo-Gangetic Plains	12.84	1.75	8.46	1.57	7.61	1.66	10.69	1.77	14.92	1.89	20.57	2.09	24.36	1.94
North-Eastern India	14.51	2.65	10.63	1.99	9.16	1.86	11.87	2.36	15.56	3.00	19.01	3.66	21.11	3.87
Northern Hills	7.94	2.48	4.16	2.27	3.09	2.39	5.41	2.58	9.05	2.57	13.64	2.58	17.27	2.62
Peninsular India	18.82	1.77	17.03	1.77	16.26	1.64	17.98	1.60	20.88	1.74	23.40	1.99	24.43	2.33
	October		November		December		January		February		March		April	
	Max. temp.		Max. temp.		Max. temp.		Max. temp.		Max. temp.		Max. temp.		Max. temp.	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
Central India	30.25	2.44	26.60	3.05	25.53	3.45	29.16	3.18	33.37	2.93	38.05	2.96	39.88	3.22
Indo-Gangetic Plains	28.47	1.85	22.95	2.50	20.81	2.73	25.13	2.89	30.32	3.05	36.89	2.62	39.82	2.29
North-Eastern India	26.67	4.41	23.01	3.87	22.04	3.80	24.85	4.38	28.10	5.11	29.79	5.98	30.16	5.93
Northern Hills	21.69	2.72	16.37	2.90	14.03	2.83	17.50	3.29	21.75	3.53	27.93	3.33	31.63	2.94
Peninsular India	30.55	1.88	29.84	1.82	30.39	1.69	32.61	1.91	35.14	2.25	37.07	2.76	36.93	3.26

TABLE 2 Data description of the rainfall-related variables (in mm, log scaled).

Climatic zone	October rainfall		November rainfall		December rainfall		January rainfall		February rainfall		March rainfall		April rainfall	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
Central India	0.32	1.20	0.47	1.29	1.01	1.56	1.16	1.72	1.38	1.81	1.35	1.69	1.63	1.84
Indo-Gangetic Plains	0.16	1.10	0.83	1.54	2.14	1.57	1.82	1.81	2.07	1.76	1.59	1.48	2.05	1.52
North-Eastern India	1.22	1.66	1.01	1.56	1.25	1.69	2.53	1.38	3.27	1.44	4.47	1.43	5.32	0.82
Northern Hills	1.74	2.00	2.83	1.45	3.97	1.21	4.10	1.06	4.28	1.09	3.96	0.99	3.89	0.87
Peninsular India	2.37	1.90	0.97	1.86	0.13	1.24	0.38	1.27	1.45	1.76	2.74	1.36	3.82	1.05

the mean and standard deviation of all the KCC-related variables undertaken in the present study.

3.2 Correlation analysis

Figure 3 represents the zone-wise correlation coefficients of all the temperature-related variables. The correlation between the minimum temperature (monthly averaged) and wheat yield is negative for three regions, i.e., Indo-Gangetic, Central India and Peninsular India. The negative correlation is lowest in the Indo-Gangetic Plains region, with the lowest correlation coefficient of −0.64. Moreover, Northern Hills and North-eastern India show a positive correlation of the monthly average minimum temperature with the yield (+0.2–+0.4). In addition, among the considered months, it was found that the minimum temperature of January is the most negatively correlated compared to the other months.

The results show that the correlation between the maximum temperature and wheat yield shows a similar pattern to the minimum temperature. In Indo-Gangetic Plains, Central India and Peninsular India, the correlation is negative, indicating that the wheat yield decreases in these regions as temperature increases. In North-Eastern India and Northern Hills, the correlation is positive. In addition, the Northern Hills show a more positive correlation than North-Eastern India because of the overall lower temperature in this region. Moreover, among the considered months, it was found that the maximum temperature of January is the most negatively correlated among the other months.

Figure 4 gives the correlation coefficients between the wheat yield and the rainfall-related variables corresponding to different regions of India. The figure shows that in all the zones, the rainfall from January till April shows a negative correlation with the yield, and the negative correlation is lowest in the northeastern and Northern hills. In other cases, rainfall of other months shows no significant correlation with the wheat yield.

From Figure 4, it is noted that, all over India, the correlation between the district-wise area of cultivation and wheat yield is positive (+0.33–+0.68). Similar patterns have been observed with the irrigated area and the derived variable (irrigated area × average max. temperature). Interestingly, the regions with a higher correlation (of the area of irrigation with wheat yield) are the regions with comparatively lesser irrigated districts (North-Eastern India, Northern Hills and Peninsular India, Supplementary Figure 1B).

Figure 5 gives the correlation coefficient values among the KCC-related variables and the wheat yield. The results show that, in Indo-Gangetic Plains, the KCC query index related to variety, fertilizer use, weed management, nutrient management and cultural practices shows a weak positive correlation (+0.2–+0.3). In contrast, the query index for government schemes is noted to have a weak negative correlation with the yield (−0.24). In addition, in the Northern hills, query index regarding the varieties, weed management, nutrient management and sowing time and weather show a positive correlation (+0.4–+0.5) against the wheat yield. Furthermore, the KCC query index did not significantly correlate with the wheat yield in North-Eastern, Central and Peninsular India.

TABLE 3 Data description of the KCC-related variables (number of calls per hectare of cultivated area, scaling of ln(x) × 10E5).

Climatic zone	Weather		Plant protection		Varieties		Fertilizer use and availability		Nutrient management		Weed management		Cultural practices	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
Central India	8.41	4.31	7.82	3.12	9.09	4.03	7.57	3.65	9.13	4.09	8.90	4.45	7.51	4.23
Indo-Gangetic Plains	8.14	2.96	7.69	2.80	9.07	3.62	7.00	2.95	9.12	3.59	7.76	3.87	6.82	3.55
North-Eastern India	12.10	3.25	11.57	3.37	12.31	3.14	11.88	3.60	12.41	3.06	12.44	3.26	11.64	3.70
Northern Hills	8.99	3.84	9.16	3.85	10.88	4.08	9.74	4.28	10.87	3.92	11.89	3.67	9.37	4.25
Peninsular India	12.50	3.16	11.30	3.37	12.63	2.76	12.39	2.97	12.14	3.16	12.28	3.17	11.60	3.68

	Government schemes		Seeds		Water management		Field preparation		Bio-pesticides and bio-fertilizers		Market information		Sowing time and weather	
	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
Central India	9.50	4.81	8.49	4.70	8.02	4.62	8.73	4.67	11.75	4.24	9.03	4.81	10.17	4.81
Indo-Gangetic Plains	7.60	4.35	6.98	4.06	6.17	3.79	6.95	4.28	8.90	5.15	6.47	4.47	8.07	5.13
North-Eastern India	12.83	2.75	12.22	3.45	12.28	3.52	12.49	3.14	13.43	1.94	13.19	2.42	13.13	2.49
Northern Hills	11.01	4.27	10.82	4.31	10.96	4.40	10.61	4.48	12.73	3.16	11.89	4.02	12.07	3.71
Peninsular India	13.46	1.84	12.45	3.05	12.55	3.22	12.63	2.93	13.29	2.17	12.08	3.45	12.36	3.13

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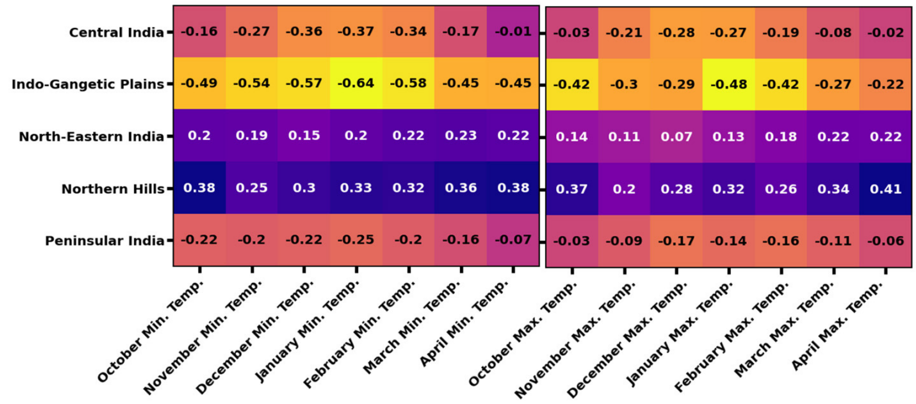

FIGURE 3
Pearson correlation coefficient values calculated zone-wise for the temperature-related variable in relation to wheat yield.

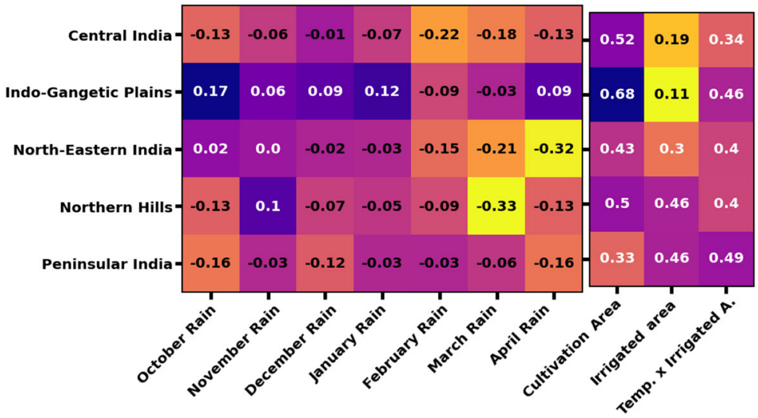

FIGURE 4
Zone-specific Pearson correlation coefficient values between the rainfall-related variable and wheat yield.

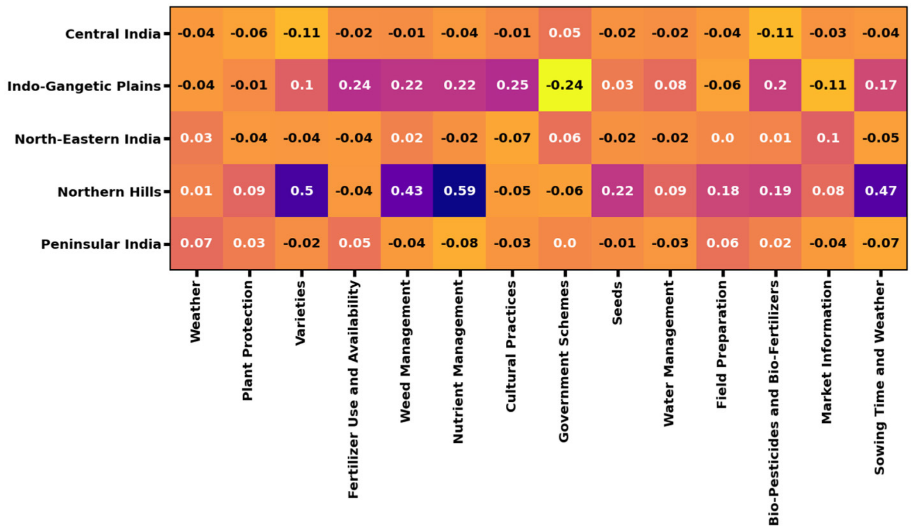

FIGURE 5
Zone-specific Pearson correlation coefficient values between the KCC-related variable and wheat yield.

TABLE 4 Zone-wise data variation captured by first three PCs corresponding different types of variables.

Climatic zone	Min. temp.	Max. temp.	Rainfall	KCC
Northern Hills	75.3%	97.7%	96.1%	98.3%
Indo-Gangetic Plains	82.5%	94.0%	92.9%	96.5%
Central India	75.3%	95.1%	94.8%	94.9%
North-Eastern India	97.9%	98.1%	98.4%	85.9%
Peninsular India	92.2%	96.1%	97.7%	55.6%
Average	**84.6%**	**96.2%**	**95.9%**	**86.2%**

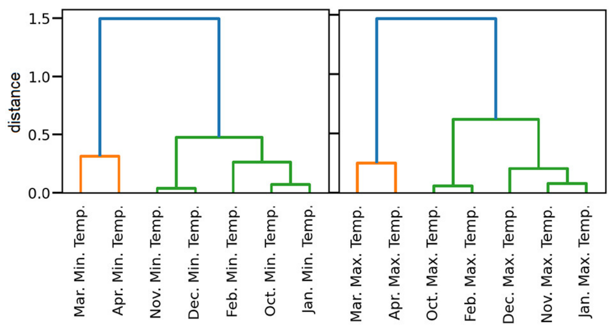

FIGURE 6
Grouping attributes through Principal Component Analysis (PCA) of the temperature-related variables.

3.3 Principal component analysis

In the presented study, PCA was performed on two aspects of the data, i.e., zone-wise PCA to identify the variables that explain the most variance in each zone and attribute-wise PCA to obtain the variables that capture the most variation among the different groups of attributes. Table 4 gives the zone-wise data variation captured (in %) by the first three PCs. Here, the analysis is done for each group of variables separately. The table shows that, on average, the variables corresponding to max. temp. can capture the most variance (96.2%) by their first three PCs, followed by the rainfall-related variables (95.9%), KCC-related variables (86.2%) and min. temp.-related variables (84.6%).

For an in-depth understanding of the effects of the considered variables on wheat yield, the variables are clustered (group-wise, i.e., rainfall, temp., and KCC) based on the PCA results. The PCA on the monthly minimum temperature data reveals that the variance in the data captured by the March and April months is similar (Figure 6). Additionally, the monthly minimum temperatures in November and December and October and January exhibit similar variances in the data. A similar pattern is reflected in the maximum temperature data points as well, max. temp. of March and April capture similar variances. Moreover, the

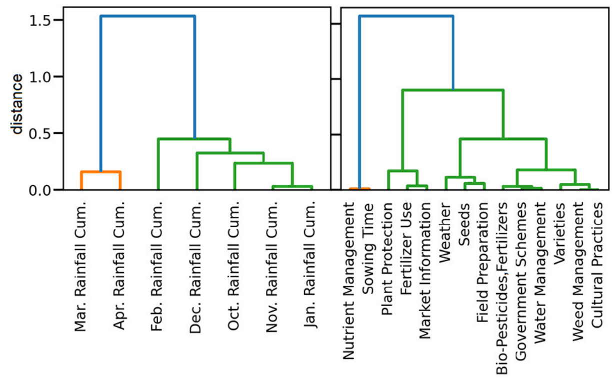

FIGURE 7
Attribute clustering using Principal Component Analysis (PCA) on the variables related to rainfall and Kisan Cal Centers (KCC).

variables corresponding to the max. temp. of the October, February, and November and January months are clustered together. The PCA of rainfall-related variables indicates that the monthly rainfall of March and April have a similar variance in the data (Figure 7). Additionally, the variance of the rainfall data for November and January is also similar.

The PCA on the attributes related to the Kisan Call Center revealed that the query index for Nutrient Management and Sowing Time and Weather had similar variance (Figure 7). Additionally, queries regarding Plant Protection, Fertilizer Usage, and Market Information could be grouped. Furthermore, the variance captured by the query index for Weather, Seeds, and Field Preparation was similar. The PCs cluster together queries about Water Management, Government Schemes, and Bio-Pesticides/Bio-Fertilizers.

The presented study also calculates the PCs zone-wise for all combined variables. The results found that the most contributing factors in each of the PCs corresponding to the Indo-Gangetic Plains include the monthly rainfall of December, January and February. Similarly, the PCA of the data corresponding to Central India shows that the attributes with the highest participation in the PCs are the monthly rainfall data for February, March and April, respectively. The results of the PCA conducted in North-eastern India reveal that the first three PCs can account for 97.4% of the total variance of the data points. Additionally, the most influential factors in these PCs are similar to those found in the analysis of North-Eastern India, which include the monthly rainfall values of February, March, and April. The PCA of the data from the Northern Hills region indicates that the key contributing factors to these PCs are the same as those found in the Indo-Gangetic Plains, which are the monthly rainfall of December, January, and February. The PCA of data from Peninsular India reveals that the most essential factors in each of these PCs include the monthly rainfall of October, November, and April.

3.4 Model development and validation

Table 5 gives the architecture of the final models obtained after hyper-parameter tuning using a grid search-based approach. Figure 8 compares different ML/DL-based models in terms of their prediction on the testing dataset. The lower the values of RMSE and MAE, the better the model performs. The figure shows that the GRU-based model has the lowest RMSE and MAE values, indicating that it performs the best among the four models. The XGB model has slightly higher values for both metrics, indicating that its performance is slightly worse than the GRU model's. The 1-D CNN and MLP models have the highest values for both metrics, indicating that their performance is worse than the others. In addition, the Diebold-Mariano test on the outputs of the models shows that the estimation of 1-D CNN and GRU-based models have no significant differences. In comparison, all the other models' outputs are significantly different. Figure 9 illustrates each model's outputs (actual vs. predicted) along with their R^2 values. Here, the x-axis represents the actual wheat yield, and the y-axis represents the predicted wheat yield by the models (scaled from 0.0 to 1.0). The graph shows that the models can capture the variations and estimate the yield precisely with the highest R^2 value of 0.75 (GRU model).

TABLE 5 Hyperparameters of the developed forecasting models (X_N, X_C, and X_G represent X number of neurons, filter size of 1D convolutional layer and the number of GRU cells present in the corresponding layer of the model, respectively).

Model	Input layer	Hidden layer(s)	Output layer
GRU	36	36_G	1_N
MLP	36	10_N	1_N
CNN	36	16_C, 8_C, 4_C, 2_C, 3_N	1_N

Figure 10 presents the Bayesian Information Criterion (BIC) values for the four undertaken models. Lower BIC values indicate better model fit and parsimony. Therefore, among the models listed, the CNN model has the lowest BIC value (−5,313.06), suggesting that it is the best-fitting model considering both goodness of fit and complexity. The GRU-based model also has relatively low BIC values compared to the CNN model, indicating that they provide better fits to the data. The XGB and MLP-based model has the highest BIC values (−4,654.37 and −4,658.91,

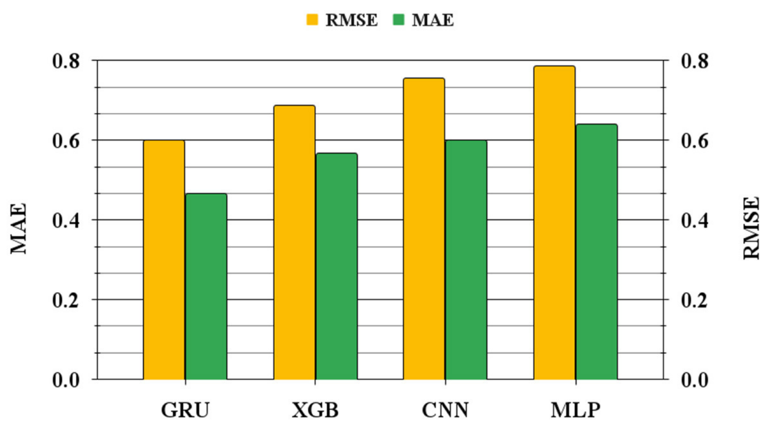

FIGURE 8
Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) values in units of t/ha associated with each model on the testing dataset.

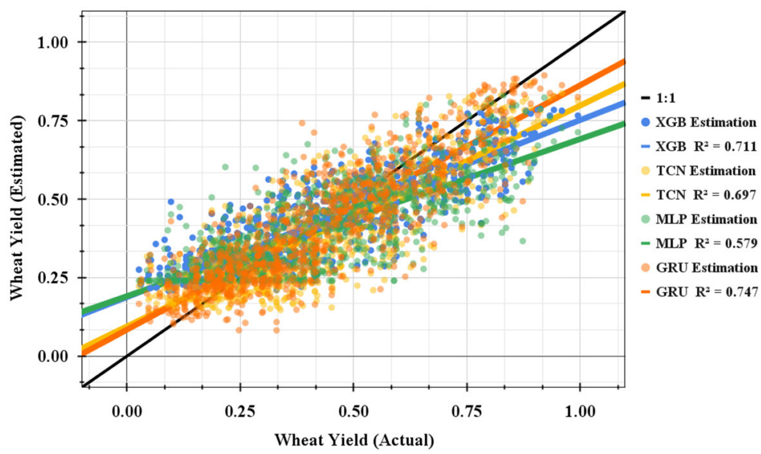

FIGURE 9
Comparison of actual vs. predicted scaled (0–1) wheat yield values for each model, along with their respective R-squared (R^2) scores.

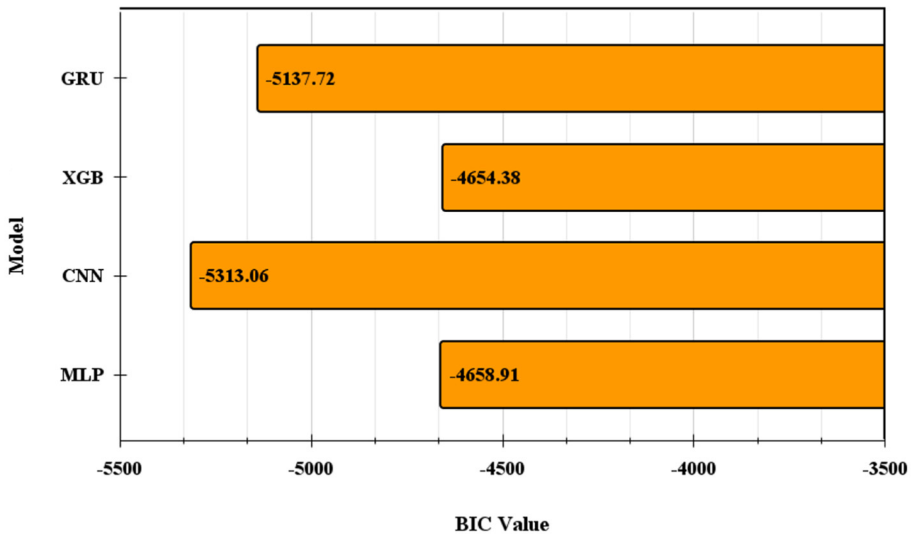

FIGURE 10
Bayesian Information Criterion (BIC) values associated with each model on the testing dataset.

respectively), indicating that these models have the poorest balance between model fit and complexity among the four models listed.

3.5 Partial derivative analysis

A partial derivative measures how much a function (wheat yield) changes when one of its variables changes while the other variables are held constant. The sign of the values indicates whether the factor has a positive or negative impact on the wheat yield in the target region. The magnitude of the values indicates the strength of the relationship between the factor and the yield. Supplementary Table 3 gives the values of the centroid points (values of the zone-representative districts) corresponding to each cluster.

Figure 11 gives the PDs of the monthly averaged minimum temperature corresponding to each considered zone. The figure shows that minimum temperature has a positive PD in North-Eastern India from December to February. Interestingly, the lowest negative partial derivatives are noted for the same months in the Indo-Gangetic region. Furthermore, it seems that the min. temp. the initial months of the season have more or less a positive PD on wheat yield all over India except the North-Eastern region, while the min. temp. the medial months seem to have a negative PD in the same regions (opposite for North-Eastern India).

The month-wise zone-wise PD regarding the averaged monthly maximum temperature concerning the wheat yield is also given in Figure 11. According to the results, it appears that in general, the regions with the highest positive partial derivatives for average monthly maximum temperature are Central India, Indo-Gangetic Plains, Northern Hills, and Peninsular India. The region with the lowest negative partial derivative is the North-Eastern region (≈-0.2).

The high temperature positively affects wheat yield in the initial months (Oct.-Nov.) of the season all over India. On the other hand, from the mid-season till the end of the season, most regions show a negative effect on wheat yield of the increased temperature (except Northern Hills and North-Eastern India).

Figure 12 gives the partial derivatives concerning the monthly cumulative rainfall each month (October-April). The highest positive partial derivatives are found for February (North-Eastern India, 0.015), January (Central India, 0.008), and December (Peninsular India, 0.004). In addition, the lowest negative partial derivatives are found for November and December in the Northeastern region of India (–0.06 and –0.02, respectively) and in February in the Indo-Gangetic Plains (–0.02). This shows that in most regions of India (excluding North-Eastern India), the initial months' rainfall (November-December) benefits wheat production. Whereas the rainfall at the end of the season generally harms the yield.

Figure 13 gives the PD of the KCC-related variable. The highest value in the figure is for Questions related to Bio-Pesticides and Bio-Fertilizers in North-Eastern India, with a value of 262.49. The second highest value is for the questions related to Market Information in the same zone, with a value of 77.52. The third highest value is for the questions related to Field Preparation in Indo-Gangetic Plains, with a value of 35.45. The three lowest (negative) partial derivative values in the table are for the questions related to Government Schemes, with a value of –32.88; questions related to Water Management, with a value of –28.56; and questions related to Nutrient Management, with a value of –6.10.

4 Discussion and policy recommendations

This section comprehensively analyzes the study's findings and discusses the probable reasons behind the observed results. Additionally, references to existing studies are provided to validate and support the findings presented in this study. The obtained

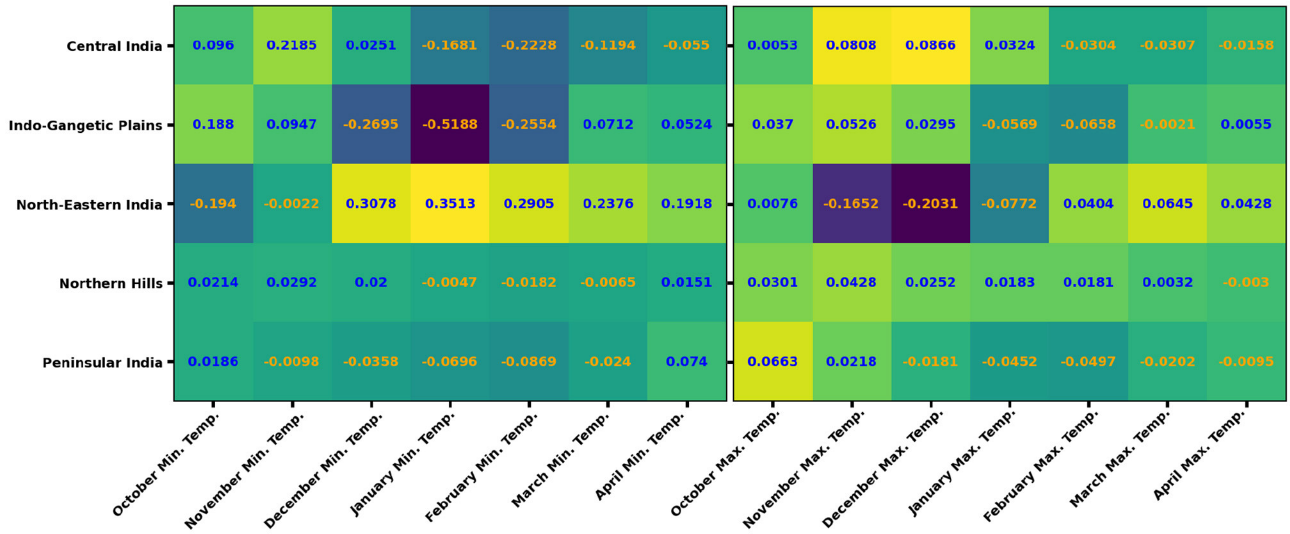

FIGURE 11
Computed partial derivatives with respect to temperature-related variables for each specific zone.

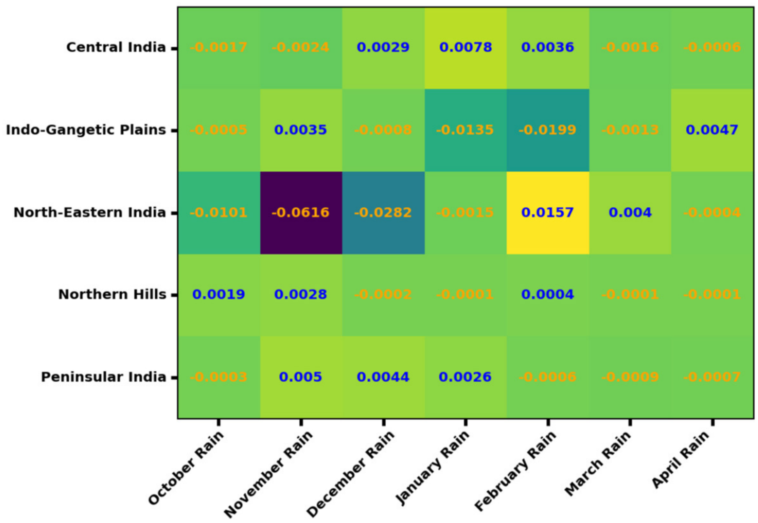

FIGURE 12
Determined partial derivatives pertaining to the rainfall-related variables for each individual zone.

results in the presented study indicate that rainfall in February, March, and April harms wheat yield in all regions, which may be because excessive rain during these months can lead to water logging, disease and pest infestation, and reduced sunlight, which can negatively impact the growth of the wheat crop (Madhukar et al., 2022; Singh et al., 2023). Therefore, it is more important that farmers should be informed about water management techniques in these particular months. Table 6 gives zone-wise policy recommendations on the type of intervention required for improving wheat yield in the respective region.

From the analysis, it was noticed that in many regions, the rainfall in the initial months positively affects the wheat yield. The reasons behind these observations are that this period corresponds to the growing season for wheat in these regions, and the amount of rain received during these months is likely to benefit the growth and development of the wheat plants (Zaveri and Lobell, 2019). Overall, the values of the partial derivatives suggest that an optimal amount of rainfall during the wheat cultivation period is crucial for good yield. In addition, the farmers from different zones must be helped at different times of the year regarding water management and other technologies, as given in Table 6.

In Central India, Indo-Gangetic Plains and Peninsular India, the correlation between the average minimum temperature and wheat yield is negative, indicating that lower daily minimum temperatures during the season are favorable for wheat growth (Madhukar et al., 2021). In contrast, the positive correlation in

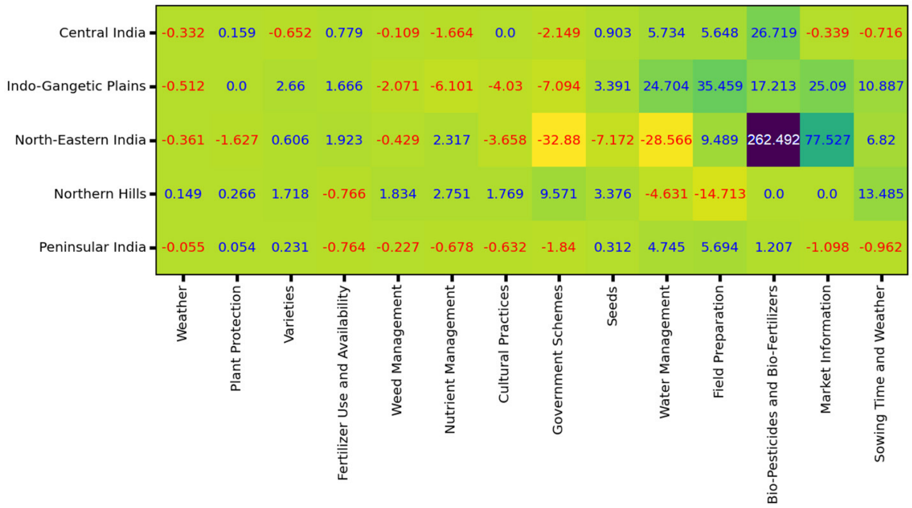

FIGURE 13
Computed the partial derivatives with respect to KCC-related variables for each distinct zone.

TABLE 6 Policy recommendations tailored to specific clusters based on the results obtained.

Climatic zone	Intervention type			
	Water management	Plant protection	Moisture conservation	Weed management
Central India	Nov.–Apr.	Jan.–Mar.	Oct.–Nov.	Oct.–Dec.
Indo-Gangetic Plain	Nov.–Apr.	Jan.–Mar.	Oct.–Dec.	Nov.–Jan.
North-Eastern India	Oct.–Mar.	Feb.–Apr.	Oct.–Nov.	Nov.–Jan.
Northern Hills	Oct.–Mar.	Feb.–Apr.	Nov.–Dec.	Oct.–Feb.
Peninsular India	Nov.–Feb.	Dec.–Feb.	Nov.–Mar.	Oct.–Dec.

North-Eastern India and Northern Hills suggests that higher daily maximum temperatures during the whole season are favorable for wheat growth in these regions (Asseng et al., 2011). Additionally, regions with high humidity, such as Indo-Gangetic Plains, may have a lower tolerance to high temperatures, hence the negative correlation (Birthal et al., 2021; Bhardwaj et al., 2022). These observations indicate that the wheat yield may be positively affected due to global warming in the Northern Hills and North-Eastern India, whereas, in other regions, it may harm wheat yield. This could be due to several reasons. For example, lower temperatures favor wheat growth and development, while higher temperatures stress the plants and decrease yields (Madhukar et al., 2021). However, the Northern-Hilly region is already a cold climatic region for wheat; therefore, higher temperatures may benefit wheat yield in these regions in the future (Madhukar et al., 2021).

Similar observations are obtained from the monthly averaged maximum temperature variable analysis. The results show that the correlation between wheat yield and average monthly maximum temperature is primarily negative in Central India, Indo-Gangetic Plains, and Peninsular India. This suggests that the wheat yield should decrease in these regions as the temperature increases. One possible reason for this observation is that high temperatures can cause plant stress, leading to decreased photosynthesis and lower yields (Hu et al., 2020). High temperatures can also increase water loss through transpiration, decreasing yields (Asseng et al., 2011). Another possible reason for the negative correlation between temperature and yield is that high temperatures promote the growth of pests and diseases, which can damage crops (Bajwa et al., 2020).

From the analysis of the KCC-related variables, it was found that farmers' demand for help in particular topics is strongly related to wheat yield. The possible reasons behind the observed values could be a combination of various factors such as the specific crop grown in each region, the weather conditions, the availability of resources, the type of farming practices used, and the level of government support (Kumar et al., 2015). For example, in Central India, there is a negative correlation between the demand for information related to weather and wheat yield.

In contrast, in the Northern Hills, a positive correlation exists between wheat yield and the demand for information related to weed management, nutrient management and wheat varieties. This could be because the farming practices used in the Northern Hills may be more susceptible to weed growth, and farmers in this region may require more information regarding technologies like fertilizer usage and the latest varieties (Yogi et al., 2023).

Similarly, in the Indo-Gangetic Plains, there is a positive correlation between the demand for information related to fertilizer usage, weed management, nutrition management, cultural practices and wheat yield. The reason is the farming practices used in the Indo-Gangetic Plains may benefit more from these technologies than other regions, and farmers may require more information to access and use such technologies effectively (Kumar et al., 2015; Yogi et al., 2023). Overall, the study results provide a snapshot of farmers' specific needs and concerns in different regions of India and can be used to inform targeted outreach and education efforts to support farmers in these regions.

The study also shows that the irrigation area positively impacts wheat production, which has already been reported in multiple studies (Zaveri and Lobell, 2019; Birthal et al., 2021). Moreover, it will be more beneficial in India's Peninsular, North-Eastern and Northern-Hilly regions to focus on developing the command area (irrigation systems). In addition, it was also found that the derived variable (max. temp. × irrigated area) has a higher positive correlation with the wheat yield (Figure 4). This suggests that it is more beneficial if the farmers irrigate the land in the seasons with higher temperatures, as high temperatures harm productivity (Birthal et al., 2021).

The experiments related to model training give us interesting information on the undertaken models. The study showed that the GRU-based model is best suited for the task at hand compared to the other models. The probable reason is it has been specifically designed to handle sequential data. Moreover, the XGB-based model also has a specific architecture for handling a variety of datasets. Still, its performance is slightly worse than the GRU-based model due to fewer training variables, differences in implementation or hyperparameter tuning. Whereas, the CNN and MLP-based models may not be as well-suited for the task at hand as they are not explicitly designed for such sequential data and may not be able to effectively learn the underlying patterns in the data (Kamilaris and Prenafeta-Boldú, 2018). The data used to train and evaluate the models may have specific characteristics that make it more difficult for some models to learn.

The PD analysis on the KCC-related variables shows that the wheat yield is greatly affected by the number of questions asked by the farmers. Moreover, it is to be noted that there are two primary reasons behind farmers asking more questions related to a particular topic. First, the farmers are more interested in gaining information on a particular topic for increasing their yields. In this case, the more questions correspond to higher crop yield. And second, the farmers are looking for solutions related to a particular topic to save the damage. In this case, the more questions correspond to lower crop yield. For example, in the case of questions related to water management by the farmers of Indo-Gangetic plains, it seems that if farmers ask more questions related to water management techniques, it will have a positive effect on the yield, the reason being they have been asking such questions to improve the yield in the past. In contrast, the PD corresponding to the same topic is negative in the North-Eastern region because the farmers only ask more questions about this topic when they face damage due to poor water management practices. Based on the findings of the research work, the following policy recommendations can be made:

- Management of rainfall and temperature: Emphasize appropriate irrigation management practices during months when the monthly rainfall and temperature variance is high.
- Climate-resilient agriculture practices: Encourage adopting climate-resilient agriculture practices to reduce the impact of extreme weather events on crop production.
- Farmer's information needs: Address the information needs of farmers regarding sowing time and weather, plant protection, fertilizer usage, and market information.
- Agriculture extension services: Strengthen the agriculture extension services by providing relevant and timely information on water management, government schemes, and bio-pesticides/bio-fertilizers.

This research work's implications are significant for agricultural practitioners and policymakers. Firstly, the analysis of month-wise environmental factors on wheat yield can aid farmers in making informed decisions regarding crop management strategies, such as irrigation and timing of planting. Secondly, understanding the relationship between farmers' demand for information and yield can guide the development of targeted agricultural extension services to meet the specific needs of farmers, potentially improving overall productivity. Finally, integrating diverse datasets and utilizing deep learning models provide a powerful tool for accurate yield prediction, facilitating better resource allocation and planning at both local and national levels.

While the research work presented in this study has notable contributions, it is essential to acknowledge its limitations. Firstly, analyzing month-wise environmental factors on wheat yield may only capture some possible variables affecting crop productivity, such as pest infestations or soil nutrient levels. Moreover, while insightful, the partial derivative-based factor analysis may oversimplify the complex interactions among various factors influencing wheat yield. These limitations should be considered when interpreting and applying the findings in practical contexts.

5 Conclusion

In the presented work, various data sources were collected and analyzed, including daily grid-wise rainfall, daily grid-wise minimum and maximum temperature, Kisan Call Center data, district-wise area of cultivation, and wheat yield. Correlation and PC analysis were conducted to identify the most significant (month-wise) factors affecting the wheat yield. The findings from the analysis showed that monthly rainfall and temperature of particular months have significant impacts (positive and negative) on wheat yield. Furthermore, in the study, four ML/DL-based models were developed to predict the wheat yield and their performance was evaluated using RMSE and MAE. The results showed that the model developed using GRU had an excellent performance in predicting wheat yield with the considered variables. The partial derivatives were calculated to determine the effect of different factors on wheat yield. The results from the analysis can be used to formulate policies related to rainfall and temperature management practices, information demand from farmers and other related factors. The research findings can also be linked to climate change as the changing weather patterns significantly impact agriculture and food security. The future scope of the presented work includes further analysis of the effect of other factors, such as soil fertility and crop disease, on wheat yield and exploring the use of advanced DL techniques for more accurate predictions. Additionally, incorporating different climate and agricultural data, such as drought indices and cropping patterns, could provide further insight into the relationship between climate change and wheat yield.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://kcc-chakshu.icar.gov.in.

Author contributions

SG: Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing—original draft. PB: Conceptualization, Data curation, Methodology, Project administration, Writing—original draft. GA: Conceptualization, Formal analysis, Software, Supervision, Validation, Writing—original draft. MA: Investigation, Methodology, Project administration, Resources, Writing—original draft. RB: Data curation, Funding acquisition, Investigation, Supervision, Validation, Writing—original draft. AJ: Data curation, Investigation, Methodology, Project administration, Writing—review & editing. RP: Software, Supervision, Validation, Visualization, Writing— review & editing. SM: Data curation, Funding acquisition, Project administration, Resources, Software, Writing—review & editing.

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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.

The reviewer HS declared a shared parent affiliation with the authors SG, GA, RP, and SM to the handling editor at the time of review.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1357201/full#supplementary-material

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Improved nursery practices and farmers' willingness to adopt heat-tolerant tomatoes under tropical conditions

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Heat-tolerant tomato (*Solanum lycopersicum* L) can be used to alleviate the impact of climate variability, increase productivity, and increase income of smallholder vegetable farmers under tropical conditions. Adoption of improved nursery practices and willingness to adopt heat-tolerant tomato varieties under tropical conditions was examined. Using data from 432 tomato farmers, multivariate probit and tobit regression models were used to assess willingness to adopt heat-tolerant varieties and number of nursery practices. Willingness to adopt heat-tolerant tomato varieties was positively influenced by education, experience, and extension contacts. Adoption of improved nursery practices was influenced by sex, household size, off-farm income, credit, education and extension. These results will enable decision-makers to prioritize strategies that target educated farmers with more years of experience in tomato production and have contacts with extension to enhance the adoption of heat-tolerant tomato seeds with complementary improved nursery practices to increase productivity and income of smallholder tomato farmers under tropical conditions.

KEYWORDS

***Solanum lycopersicum*, climate variability, multivariate probit, tobit model, Ghana**

Introduction

Erratic nature of rainfall pattern has resulted in highly seasonal nature of tomato (*Solanum lycopersicum* L.) production (Robinson and Kolavalli, 2010). This results in high price, high demand, and fluctuating output which have serious implications for income of smallholder farmers. Production mainly depends on family, rented, or land of relatively small sizes (less than 2 acres; Monney et al., 2009). In spite of the importance of improved seed in improving yield, smallholder farmers in Ghana still cultivate local varieties (Robinson and Kolavalli, 2010; FAO, 2016). Varieties commonly grown in Ghana include Roma VFN, Pectomec VF, Tropimec, Rion Grande, Jaguar, Lindo, Titao Derma, Ada Cocoa, Laurano, Raki, Choco TP, Power Reno, Rasta, and Italy Heinz (Ministry of Food and Agriculture (MoFA), 2010; FAO, 2016). Farmers tend to accept, and adopt, recommended varieties and practices due to yield benefits, matching with existing farming system, and simple to use (Al-Shadiadeh et al., 2012; Danso-Abbeam et al., 2012).

Farmers are more inclined to accept, and adopt, recommended varieties and practices due to yield benefits when compared with existing varieties (Al-Shadiadeh et al., 2012; Danso-Abbeam et al., 2012). The rate of adoption of a technology depends on the characteristics of individual farmer's production circumstances, characteristics of technology, socioeconomic characteristics of farmers, and speed with which the population is made aware of the technology and its application to local production systems (Siziba et al., 2011; Etwire et al., 2013; Xaba and Masuku, 2013; Sanusi and Dada, 2016). Improved nursery practices in tomato production are necessary to increase vigor, growth, and efficient productivity (Thakur and Tripathi, 2015; Easdown and Ravishankar, 2016). However, the adoption of these practices is low among local smallholder tomato producers (Ministry of Food and Agriculture (MoFA), 2016). Promoting adoption of improved nursery practices is important for efficient production. However, the adoption of these practices is low among smallholder tomato producers (Ministry of Food and Agriculture (MoFA), 2016).

Studies have examined the adoption of improved production practices (Asante et al., 2013; Huat et al., 2013; Masood et al., 2018; Frimpong et al., 2021; Gotame et al., 2021; Nkansah et al., 2021; Shrestha et al., 2021; Iqbal et al., 2022; Akomdo et al., 2023). Most of these studies focused on the agronomic effects (Masood et al., 2018; Gotame et al., 2021; Shrestha et al., 2021; Iqbal et al., 2022), while others investigated such adoption decisions under different production settings. For instance, Nkansah et al. (2021) examined the influence of topping and spacing on growth, yield, and fruit quality of tomato under greenhouse condition. Frimpong et al. (2021) examined the relationship between sociodemographic, institutional factors, and adoption of best tomato production practices in Southern Ghana. However, the study focused on the relationship between such factors, without any attempt in estimating the determinants of adoption of these practices. To the best of our knowledge, a study examining farmers' adoption of improved nursery practices and their willingness to adopt improved heat-tolerant tomatoes under tropical conditions has not been explored. This study examines this nexus and investigates the willingness decision of rural tomato farmers to adopt heat-tolerant tomato varieties under tropical conditions and provide vital policy insights for enhancing the tomato industry, especially in the midst of climate variability in order to enhance the welfare of rural farmers.

Thus, the findings of this study present a better understanding of the underlying factors, influencing low adoption, and presents useful insights into guiding policy for enhancing local tomato production. Given that farmers in Ghana still produce local varieties, the findings also present an opportunity to develop locally adapted improved varieties that are high yielding and tolerant to biotic and abiotic stresses, to meet the increasing demand for the fruits both for local industry and fresh consumption.

This study examines the drivers of adoption of improved nursery practices and estimates farmers' willingness to adopt heat-tolerant tomato varieties in Ghana. We contribute by providing empirical evidence on the drivers of adoption of improved nursery practices for enhancing policies to improve tomato production in Ghana. Such information is essential for the tomato sector because of the vital role nurseries play in open field production and its implications in the entire tomato value chain. In addition, our result provides empirical insights of the factors influencing farmers' willingness to adopt heat-tolerant tomato varieties. Such information is essential for research on crop movement programs, especially tomato breeders in the development of improved varieties with such attributes as part of the characteristics to consider. Finally, the findings will provide useful insights for policymakers in designing agricultural policies aimed at enhancing the adoption of improved nursery practices and heat-tolerant varieties for improving tomato production in the country to meet local demand for consumption and processing.

The rest of the study is structured as follows. The next section presents the methodology which includes a description of the study area, data, sampling, and the empirical strategy for the analyses. The next section presents the results and discussions, and the final section presents the conclusions and policy recommendations.

Methodology

Study area

Basically, Ghana has six agroecological zones with various ranges of climatic, vegetation, and soil types. These zones are categorized into tropical rainforest, semi-deciduous forest, forest savannah transition, coastal savannah, Guinea savannah, and Sudan and Sahel savannah. Thus, the study was conducted across four out of the six major agroecological zones, namely, Guinea savannah, forest savannah transition, coastal savanna, and the Deciduous Forest agroecological zones.

The Deciduous rainforest, forest savannah transition, and costal savannah zones are characterized by bimodal rainfall pattern, resulting in major and minor cropping seasons. Mostly, forest savannah transition and deciduous forest agroecological zones cover the Bono, Ahafo, and Ashanti regions with an exceptional environment that is favorable to the production of various crops and livestock (Ghana Districts Repository, 2020). Averagely, the zones recorded annual rainfall between 1,200 and 1,400 mm and temperature of 25°C with favorable climatic and social factors that boost the cultivation of huge volume of crop varieties (Ministry of Food and Agriculture (MoFA), 2019).

In the Guinea savanna zone, approximately 80% of the land in the forest- savanna transition region is used for crop and livestock production. The zone records a unimodal rainfall pattern, resulting in a single growing season and enhancing several crops thrives well in this zone such as tomato, maize, rice, cowpea, groundnuts, and yam cassava. Across the four agroecological zones, tomato production is a major economic activity in the resident population.

Data were collected from the Offinso, Techiman, and Tano South districts in the Bono and Ahafo regions under the forest transition agroecological zones. In addition, the Asante Akim Agogo and the Mampong districts under deciduous forests, Kassena-Nankana district under Guinea savanna, and Ada West and Agotime districts under coastal savannah were involved. These districts were selected because they are the important for tomato production in the country. The majority of the tomato produced in Ghana can be traced from these districts.

Data and sampling

A multi-stage sampling technique was employed to sample and interviewed 432 smallholder tomato farmers. In the first stage, the four agroecological zones, namely, forest, transitional, coastal, and Guinea Savannah, were purposively selected based on the prevalence of tomato production and the dominance of tomato producing rural farm households in these agrological zones. From each of the selected agroecological zone, four districts were also purposively selected to reflect the high tomato production trends in the zone. From each district, two tomato producing communities were purposively selected from a list of tomato producing communities. From each community, a maximum of 30 tomato producing households were randomly selected and interviewed using a semi structured questionnaire to obtain the primary data used in this study. Data collected comprised demographic, production, input, and output quantities and prices.

Empirical strategy

Data collected were analyzed and summarized using descriptive statistics, such as frequency, charts, graphs, and tables. To understand the factors influencing willingness to adopt heat-tolerant varieties of tomatoes, the binary probit model was used, while the multivariate probit regression model and tobit models were applied to estimate the factors influencing the adoption of improved nursery practices. These methods are discussed in detail in the following paragraphs.

Examining the factors influencing the adoption of heat-tolerant tomato varieties

To examine the factors influencing the adoption of the nursery practices of tomato farmers, a probit model was used (Rahm and Huffman, 1984). In this case, the utility obtained if they adopt nursery practice is greater than that for non-adopters, i.e., $(U_{i1} > U_{i0})$. This response is a binary one, and the outcomes are mutually exclusive.

The binary probit model

The binary dependent variable, Y_i assumes the values "1" if a farmer is willing to adopt the heat tolerant variety, "*adopter*" and "0" if otherwise. Thus, this is represented as a function of the demographic characteristics and institutional factors X (such as age, sex, years of schooling, household size, tomato experience, number of plots, off-farm income, credit access, extension visits, distant to extension office, FBO membership, and IP membership) and an error term with mean of zero stated in Equations (1) and (2) below:

$$U_{i1}\left(X\right) = \alpha_1 X_i + \delta_{i1} \text{ for adopter} \tag{1}$$

$$U_{i0}\left(X\right) = \alpha_0 X_i + \delta_{i0} \text{ for non} - \text{adopter} \tag{2}$$

Thus, observing a value of 1 will generate probability,

$$P_r = \left(Y_i = 1 / x_i \alpha_i\right) = 1 - H\left(-x_i \alpha_i\right) \tag{3}$$

and the probability for observing 0 could be given as follows:

$$P_r = \left(Y_i = 0 / x_i \alpha_i\right) = H\left(-x_i \alpha_i\right) \tag{4}$$

where H denotes a continuous variable, strictly increasing cumulative distribution function and thus taking a real value and returns a value which ranges from 0 to 1.

Thus, we estimate the parameters in the models in equations (3) and (4) through the maximum likelihood estimation (MLE) procedure. The dependent variable is an unobserved latent variable and is expressed in Equation (5) as follows:

$$Y_i \text{ as } Y_i = \alpha_j X_{ji} + \delta_i \tag{5}$$

where δ_i is a random error term.

The observed dependent variable is determined by whether the predicted Y^* is greater than 1 or otherwise as specified in Equation (6) as follows:

$$Y_i = 1 \text{ } if \text{ } Y_i^* > 0 \text{ and } Y_i = 0 \text{ } if \text{ } Y_i^* \leq 0 \tag{6}$$

where $Y_i^*$is the threshold value for $C_i$and is assumed to be normally distributed.

The probit model adopted for the study is expressed in Equation (7) as follows:

$$P_i = P(Y_i^* < Y_i) = P_i = P(Y_i^* < \alpha_0 + \alpha_j X_{ji}) \tag{7}$$

where P_i is the probability that an individual will make an objective decision by adopting "*adopter*" or not adopting "*non-adopter*" and Y_i is the dependent variable.

Estimating the adoption of improved nursery practices in tomato production

The adoption of nursery practices is multivariate in nature, thus adoption of these practices include fertilizer application, hardening, staking, pruning, and soil treatment is such that a farmer will adopt any of these practices or a combination of them that best addresses his/her production needs. In effect, the decision of the farmer whether to choose one or another underlies on information on several other practices available. Subsequently, a farmer is likely to adopt a specific practice if the benefits obtained from adoption are greater than that of non-adoption.

The multivariate probit model

The adoption of nursery practices is modeled along the random utility framework (Kassie et al., 2013; Mulwa et al., 2017). In this case, an i^{th} farmer faced the decision to adopt in a j^{th} practice where $i = 1,2,3\ldots\ldots, N$ and $j = 1,2,3\ldots.., J$, i.e., j = adoption of nursery practices, such as fertilizer application (FA), staking (SK), pruning (PR), soil treatment (ST), and hardening (HR). Thus, we decide to let P^*signify the difference between the utility from adoption $\left(U_{iA}\right)$and the utility from non-adoption $\left(U_{iN}\right)$ of particular nursery practices. A randomly selected farmer from given household i will decide to adopt a specific nursery practice if $P^* = U_{iA} - U_{iN} > 0$. Accordingly, the benefits from adopting a specific nursery practice are a latent variable, which are determined by the observed covariates (X_i), and the error term (ε_i) is expressed in Equation (8) as follows:

$$P_{ij}^{*} = X_i^{'}\beta_j + \varepsilon_i \tag{8}$$

Therefore, the two utilities are unobservable but can be stated for each nursery practice as a function of observable components in the latent variable, which is expressed in Equation (9) as follows:

$$P_{ij} = \begin{cases} 1 & \text{if } P_{ij}^{*} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

Where P_{ij}^{*} is a latent variable that denotes observed and unobserved preferences associated with the j^{th}nursery practice, and P_{ij}denotes binary dependent variables. Xik denotes a set of household and farm-specific characteristics and institutional variables. Aik denotes plot characteristics to account for unobserved heterogeneity. β_k and α_k are estimated parameters. ε_k denotes the multivariate normally distributed stochastic error term (Wooldridge, 2003). Based on the multivariate probit model, the possibility of adopting multiple nursery practices and the error terms jointly follows a multivariate normal distribution (MVN) with zero conditional mean and variance which are normalized to unity, i.e., and the covariance matrix © is given in Equation (10) by:

$$\Omega = \begin{bmatrix} 1 & \rho_{FASK} & . & \rho_{FAHR} \\ \rho_{SKFA} & 1 & . & . \\ . & . & 1 & \rho_{STHR} \\ \rho_{SKHR} & . & \rho_{HRST} & 1 \end{bmatrix} \tag{10}$$

where ρ denotes the pairwise correlation coefficient of the error terms with respect to any two of the estimated adoption equations of the nursery practices. Consequently, the off-diagonal elements (e.g., ρ_{GM}, ρ_{MG}) in the covariance matrix denote the correlation between the stochastic components of the different nursery practices (Mulwa et al., 2017). The non-zero value of these correlations in the off-diagonal elements supports the appropriateness of the use of the multivariate probit model.

Tobit model

The tobit model is used to analyze the joint decision made by tomato farmer. Some factors influence the number of tomato nursery practices adopted by the farmers. For instance, there is a latent unobservable variable Y_i that depends linearly on $X_i$through β_i vector parameters. We have normally distributed error term $e_i$to capture random effects. Considering the dependent variable, Y_i denotes the latent variable whenever the latent variable is above zero and zero otherwise (Sindi, 2008; Chebil et al., 2009). The tobit model used in this study measures the factors influencing the number of tomato nursery practices. The tobit model is expressed in Equations (11)- (13) as follows:

$$Y_i = X_i\beta_i + e_i, e_i = N\left(0, \delta^2\right) \tag{11}$$

$$Y_i = X_i\beta_i + e_i \text{if } X_i\beta_i + e_i > 0 \tag{12}$$

$$Y_i = 0 \text{if } X_i\beta_i + e_i \le 0 \tag{13}$$

where Y_i denotes dependent variable, X_i denotes independent variable, β_i denotes vector of maximum likelihood estimated coefficients, and $e_i$denotes error term.

Explanatory variables and their *a-priori* expectations

Table 1 presents a description of the explanatory variables used in the model and their measurement and *a-priori* expectations.

Results and discussions

Results

Socioeconomic characteristics of tomato farmers

Socioeconomic characteristics of tomato farmers are presented in Table 1. A typical tomato farmer selected across these zones is on average 44 years. Tomato production is dominated by men constituting 68% with an average of 7.5 years of schooling. The majority of the farmers have completed basic schooling. Characteristically, farmers have 13.5 years of experience in tomato cultivation, implying an in-depth understanding of tomato production with an average farm size of 3.8 acres. Less than half of the farmers representing 36% engaged in off-farm income, obtaining an average of GHS2,190.3 from off-farm income generating activities (Table 2).

In addition, more than half of the farmers (73%) were found to be household heads, while almost half (49%) of them own the land under tomato cultivation.

TABLE 1 Explanatory variables in the multivariate probit model.

Variable	Measurement	Expected outcome
Age	Age of farmer (years)	+
Years of schooling	Years of formal education (years)	+
Number of plots	Number of tomato plots	+
Tomato experience	Number of years of farming tomato	+
Off farm income	Off farm income (GHS)	+/−
Sex	1 = Male, 0 = Female	+/−
Distance	Distance to extension office (km)	−
Extension visits	Extension visits (1 = Yes and 0 = No)	+
Access to credit	Access to credit during last year (yes = 1; 0 = No)	+/−
FBO membership	FBO membership (1 = Yes and 0 = No)	+

TABLE 2 Socioeconomic characteristics of tomato farmers across the regions.

Variable	Forest	Transitional	Coastal	Guinea Savannah	Overall	*F*-value
Age (years)	44.4 (11.18)	43.3 (12.37)	43.5 (12.61)	42.8 (12.56)	43.6 (12.14)	0.35
[c]Gender *(Male = 1)*	68% (0.47)	84% (0.37)	62% (0.49)	65% (0.48)	68% (0.47)	3.76***
Years of schooling	6.8 (4.24)	8.8 (3.22)	8.0 (4.39)	6.0 (5.12)	7.5 (4.50)	7.36***
Years of farming tomato	15.5 (8.64)	15.7 (9.55)	12.3 (8.02)	9.3 (7.05)	13.5 (8.68)	9.60***
Farm size (acre)	2.5 (2.44)	3.5 (3.42)	4.7 (4.50)	1.5 (0.58)	3.8 (3.41)	20.32***
[c]Engaged in off-farm income *(Yes = 1)*	25% (0.43)	27% (0.45)	53% (0.50)	25% (0.43)	36% (0.48)	9.70***
Off-farm income (GHS)	2,112.07 (1779.02)	2,868.0 (1999.31)	2,070.4 (1850.5)	1,903.6 (1501.96)	2,190.3 (2117.02)	1.69
Household size	6.6 (2.49)	7.5 (3.52)	7.3 (2.97)	7.4 (3.17)	7.2 (3.0)	2.55**
Economic active HHM	3.5 (1.71)	4.2 (2.42)	3.9 (2.18)	4.0 (1.92)	3.9 (2.10)	3.88***
Dependent HHM	3 (1.8)	3 (1.9)	3 (2.0)	3 (2.0)	3 (1.8)	0.33
[c]Household head *(Yes = 1)*	73% (0.45)	85% (0.36)	70% (0.45)	63% (0.49)	73% (0.44)	2.60**
[c]Land ownership *(Yes = 1)*	49% (0.15)	47% (0.13)	39% (0.11)	44% (0.12)	49% (0.14)	15.99***
[c]Resident status *(Indigenous = 1)*	37% (0.11)	42% (0.12)	39% (0.12)	35% (0.11)	38% (0.12)	1.24
Extension visits (times)	2.8 (2.0)	1.7 (1.0)	2.8 (2.04)	1.7 (2.91)	2.5 (2.07)	7.38***
Distance to nearest extension office (Km)	8.7 (3.56)	8.2 (4.49)	7.0 (4.38)	7.1 (3.06)	7.8 (4.10)	5.21***
Distance to tomato farm (Km)	5.2 (2.36)	5.8 (2.47)	5.1 (2.38)	3.8 (2.19)	5.1 (2.43)	6.29***
[c]Credit access *(Yes = 1)*	11% (0.32)	43% (0.50)	25% (0.44)	16% (0.43)	24% (0.43)	8.55***
Cash amount received for tomato production (GHS)	823.1 (826.79)	2,439.7 (1953.20)	1,534.0 (1400.2)	644.4 (512.71)	1,709.7 (1664.34)	4.85***
[c]Credit payment *(Yes = 1)*	92% (0.28)	89% (0.31)	100% (0.01)	88% (0.01)	94% (0.24)	1.10
[c]FBO membership *(Yes = 1)*	9% (0.29)	41% (0.49)	21% (0.41)	21% (0.41)	22% (0.41)	7.86***
[c]IP membership *(Yes = 1)*	6% (0.24)	5% (0.23)	8% (0.27)	0% (0.01)	6% (0.23)	2.05*
Frequency of cultivation per season	1.0 (0.29)	1.0 (0.26)	1.2 (0.5)	1.0 (0.29)	1.1 (1.08)	6.95***

[c]Dummy variables. Figures in parenthesis are standard deviations. *** 1% significance level; **5% significance level; *10% significance level.

Consequently, a typical tomato producing household comprised of seven members with an average of four of such members being economically active. Thus, these household members provide additional labor to support tomato production, thereby generating more off-farm income for the household. Approximately 38% of the farmers were found to be indigenes, while only 24% of them had access to credit. Surprisingly, farmers received GHS1,709.7 as credit accounting for tomato production, out of which 94% of the them were able to repay the credit received during the year. Again, membership of agricultural groups such as the FBO and Innovative Platform (IP) was very low among the tomato farmers (representing 22 and 6%, respectively) of the farmers across the regions.

Furthermore, it was found out that, on average, typical tomato farmers received three extension visits for which extension officers have to travel an average of 7.8 km to achieve this purpose. Tomato farmers cultivate more than once within the season traveling an average distance of 5.1 km to their farms.

Figures 1, 2 illustrate the distribution of educational level and marital status of tomato farmers across the various agroecological zones. The results showed that educational levels of tomato farmers varied significantly across the various agroecological zones with Pearson chi-square of 74.36 and *p-value* of 0.000. The majority of the farmers who completed basic education were found in the coastal zone (35%), followed by the forest zone with 32% and tradition zone comprising 28%, while Guinea savannah zone recorded the least. In addition, most of the farmers who have completed secondary education are found in the coastal savannah zone constituting 56%, followed by forest and transitional zones representing 15 and 13%, respectively, However, the majority of farmers (33%) in the coastal region have no formal education, followed by Guinea savannah and forest zone constituting 32 and 30%, respectively.

Marital status was found to be differed significantly across the various agroecological zones with Pearson chi-square of 48.05 and *p-value* of 0.000. Mostly, approximately 48% of the farmers were married in the coastal zone followed by 32% in the transitional and 20% in the Guinea savannah zone.

Factors influencing willingness to adopt heat-tolerant tomato varieties among farmers

The probit regression estimates of the factors influencing tomato farmers' willingness to adopt heat-tolerant tomato varieties are presented in Table 3. The results indicate that, household size, household head, years of schooling tomato experience, extension visits, and number of plots cultivated significantly influenced farmers' willingness to adopt heat-tolerant tomato varieties. Both household head and household size negatively and significantly influenced the willingness to adopt decisions. Subsequently, male household heads are less willing to adopt the heat-tolerant tomato varieties than female household heads. Years of schooling positively influenced willingness to adopt heat-tolerant tomato varieties. The result further shows that more years of experience in farming tomato production positively influenced farmers' willingness to adopt heat-tolerant tomato varieties.

Again, extension visits were found to significantly influence farmers' willingness to adopt heat-tolerant tomato varieties. Furthermore, farmers with a smaller number of tomato plots for tomato cultivation are more willing to adopt heat-tolerant varieties.

Factors influencing the adoption of improved nursery practices of tomato production

Table 4 presents the multivariate probit estimates of the factors that influence the adoption of improved nursery practices. The majority of improved nursery practices included in the model are fertilizer application, staking, pruning, soil treatment, and hardening practices.

The result shows that sex showed a positive and significant relationship at 1%. Treatment of soil prevents the soil from disease incidence such as pathogen and fungi, thus adoption of soil treatments has been found to improve and protect the soil inoculant from any kind of harm. Therefore, male tomato farmers are more likely to adopt this practice than female counterparts. Household head negatively and significantly influenced the adoption of staking, soil treatment, and hardening practices at 1, 5 and 1%, respectively. Thus, farmers who are head of the house are less likely to adopt these nursery practices (staking, soil treatment, and hardening practices).

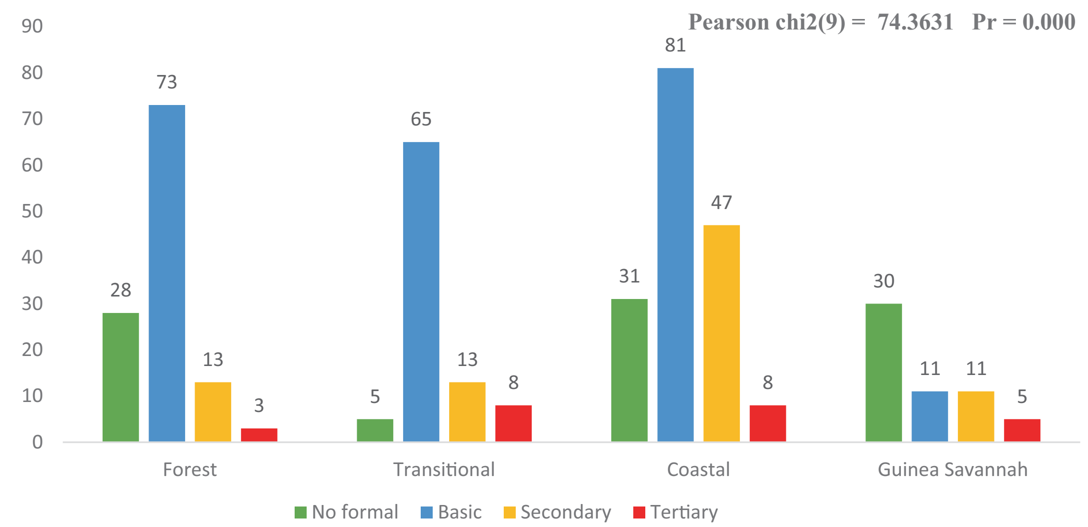

FIGURE 1
Educational level of tomato farmers across the regions.

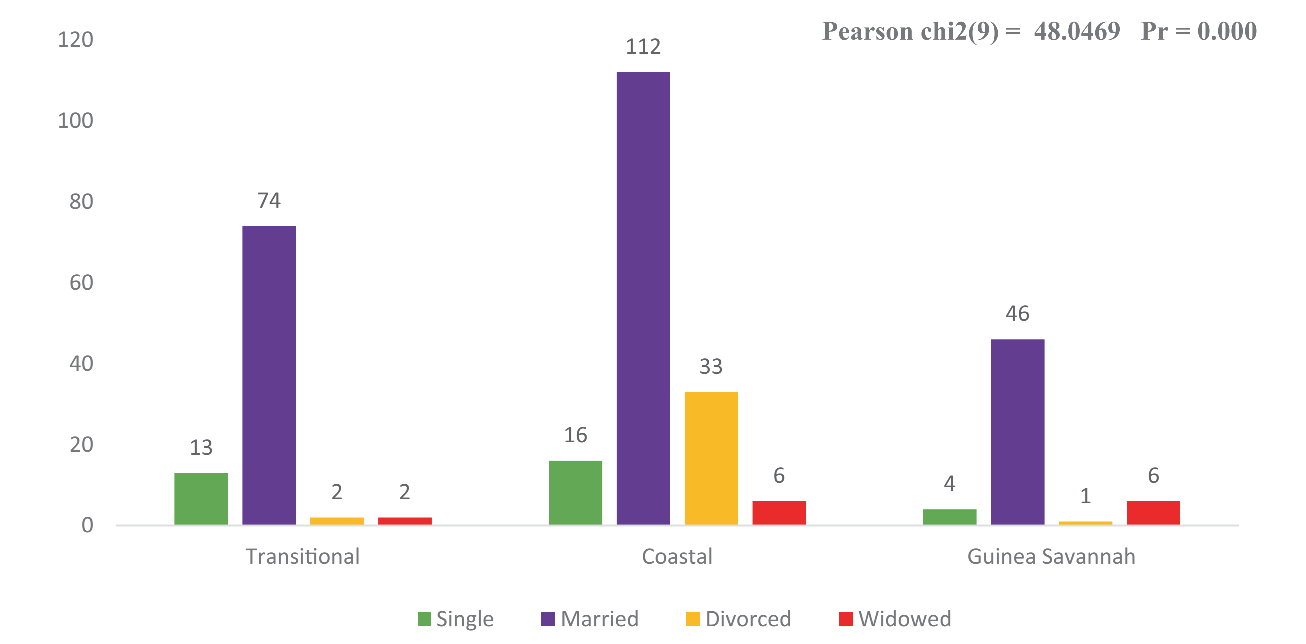

FIGURE 2
Marital status of tomato farmers across the regions.

TABLE 3 Probit estimates of the willingness to adopt heat-tolerant tomato varieties.

WTA	dy/dx	Standard Error	*t*-value
Age	0.010	0.013	0.03
Sex	0.284	0.282	1.01
Household head	−0.634*	0.333	−1.90
Household size	−0.139***	0.040	−3.48
Household member involved tomato cultivation	0.109	0.065	1.68
Years of schooling	0.132***	0.111	−1.19
Tomato experience	0.030*	0.017	1.80
Credit access	0.860	0.357	2.41
FBO membership	0.162	0.323	0.50
IP membership	0.220	0.614	0.36
Distance to extension office	0.026	0.03	0.87
Extension visits	0.116**	0.046	2.50
Number of plots	−0.349***	0.105	−3.33
Constant	2.923***	0.646	4.52
Pseudo r-squared	0.683		
Number of observations	432.00		
Chi-square	33.966		
Prob > chi2	0.000		

***$p<0.01$, **$p<0.05$, *$p<0.1$.

Years of schooling showed a positive and significant relationship between fertilizer application, pruning, and hardening practices. A typical farmer is more likely to adopt these practices due to higher number of years spent in school and ability to adopt new ideas and ways of doing things.

Furthermore, household size positively influenced the adoption of fertilizer application and marginally increased by 12 times at 1% level, while it negatively influenced the adoption of pruning practice significantly at 1% level. In addition, household member involved in tomato cultivation positively and significantly influenced the adoption of fertilizer application and pruning practices at 1 and 5% levels, respectively. Residence status of the farmers was found negatively and significantly influenced the adoption of hardening practice. Thus, the likelihood of adoption of hardening practice was less among indigenes than settlers.

The result shows that key factors influencing the adoption of improved nursery practices are sex, household head, household size, household members involved in tomato cultivation, marital status, credit access, number of plots, number of extension contacts, tomato experience, frequency of cultivation, years of schooling, and membership of innovation platforms. These factors influenced the adoption of various improved nursery practices in different magnitudes.

The variable sex had a positive significant influence only on the adoption of soil treatment before carrying out the nursery function. This implies that men are likely to apply soil treatment in their nursery preparation than women. Because of the economic value of tomato production, men tend to take keen and cautious steps to ensure that the necessary improved practices are adhered to in order to achieve increased productivity.

Being heads of households negatively influenced the adoption staking, soil treatment and hardening among the farmers. Household size and members engaged in tomato cultivation negatively influenced the adoption of both fertilizer application and pruning.

The number of tomato plots cultivated had positive effects on the adoption of three out of the five major practices, namely,

TABLE 4 Multivariate probit estimates of the determinants of adoption of improved nursery practices for tomato production.

Variable	Fertilizer application	Staking practice	Pruning practice	Soil treatment	Hardening practice
Sex	0.438 (0.285)	0.283 (0.238)	−0.188 (0.485)	0.651*** (0.218)	0.421 (0.283)
Age	0.009 (0.008)	−0.003 (0.008)	−0.003 (0.015)	0.010 (0.006)	0.058 (0.053)
Household Head	−0.055 (0.295)	−0.417* (0.232)	−0.686 (0.460)	−0.530** (0.226)	−1.741* (0.961)
Household size	0.121*** (0.040)	−0.036 (0.033)	−0.207*** (0.073)	−0.026 (0.028)	−0.134 (0.232)
Household member involved in cultivation	0.189*** (0.049)	0.065 (0.044)	0.187** (0.073)	−0.005 (0.040)	0.123 (0.149)
Resident status	0.013 (0.249)	0.098 (0.216)	0.213 (0.312)	0.047 (0.178)	−1.844** (0.750)
Marital status	0.020 (0.158)	0.106 (0.146)	0.622** (0.242)	−0.022 (0.123)	−0.235 (0.500)
Off farm income	−0.227 (0.173)	0.255 (0.181)	0.885** (0.348)	0.044 (0.146)	−0.664 (0.739)
Credit access	0.290 (0.211)	0.196 (0.170)	0.496* (0.280)	0.259 (0.166)	0.939 (0.988)
Number of plots	0.004 (0.036)	0.131*** (0.031)	0.034 (0.055)	0.034*** (0.028)	0.215** (0.098)
Extension contacts	0.121*** (0.034)	0.034 (0.031)	−0.007 (0.053)	0.011 (0.029)	0.271* (0.105)
Tomato experience	0.203 (0.137)	−0.132 (0.092)	0.260** (0.114)	0.110 (0.079)	−0.076* (0.044)
Frequency of cultivation	−0.071 (0.263)	−0.379 (0.355)	−0.696* (0.320)	−0.385** (0.180)	6.754*** (0.770)
Years of schooling	0.078*** (0.116)	−0.085 (0.112)	0.400** (0.156)	−0.132 (0.087)	0.390*** (0.205)
FBO membership	−0.005 (0.214)	0.380* (0.205)	−0.232 (0.343)	0.128 (0.176)	−0.092 (1.770)
IP membership	−0.041 (0.363)	0.289 (0.331)	0.329 (0.493)	0.394 (0.341)	9.164*** (2.583)
_cons	0.580 (0.725)	−1.532 (0.716)	−3.784*** (0.942)	1.187*** (0.526)	−6.707 (2.845)
Wald chi2(60)		187.28			
Number of observations		432			
Prob > chi^2		0.000			

Likelihood ratio test of rho21 = rho31 = rho41 = rho32 = rho42 = rho43 = 0: chi2(6) = 33.2379 Prob > chi2 = 0.0000.

staking, soil treatment, and hardening. Extension visits positively and significantly influenced the adoption of fertilizer application and hardening practices. Experience in tomato production had a positive significant influence on pruning and a negative influence on hardening. Pruning requires consistent practice and some kind of experience to implement it effectively to achieve desired results. Farmers who are members of FBO positively and significantly influenced the adoption of staking practice. Years of schooling positively influenced the adoption of three out of the five improved nursery practices, namely, fertilizer application, pruning, and hardening.

Factors influencing number of nursery practices adopted by tomato farmers

Given the importance of thee improved nursery practices in tomato productivity, to assess the intensity of use, this study further

TABLE 5 Factors influencing the number of nursery practices adopted by tomato farmers.

Nursery practices	Coefficient	Standard error	*t*-value
Age	0.214	0.171	1.26
Economically active HH members	0.11*	0.061	1.79
Year of schooling	0.276**	0.113	−2.44
Off farm income	0.124***	0.034	3.67
Tomato experience	−0.094	0.073	−1.30
Number of Plots	0.095**	0.043	2.19
Farm distance	0.147	0.167	0.88
Credit access	0.074	0.077	0.97
FBO membership	−0.107	0.088	−1.22
IP membership	0.203	0.125	1.62
Farm size	0.011	0.015	0.69
Extension visits	0.003	0.014	0.23
Distance to extension office	−0.021	0.024	−0.85
Frequency of cultivation	−0.249*	0.129	−1.93
Native	−0.111	0.099	−1.12
Guinea savannah	−0.239	0.159	−1.50
Transition	−0.301*	0.167	−1.80
Coastal	−0.374**	0.149	−2.50
Constant	−0.078	0.742	−0.11
Number of observations	432		
Pseudo r-squared	0.307		
Chi-square	41.119		
Prob > chi2	0.001		

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

examines the factors influencing the number of improved nursery practices adopted by the farmers. Table 5 presents the tobit regression estimates of the factors influencing the number of nursery practices adopted by the farmers.

The results show that the key factors influencing the number of improved practices adopted are the number of economically active household members, years of schooling, off-farm income, number of plots, frequency of cultivation, and residing in the transition and coastal savannah agroecological zones. Positive effect was found on the number of economically active household members, year of schooling, off-farm income, and number of tomato plots cultivated, whereas negative effects were found on frequency of cultivation and residing in the transition and guinea savannah agroecological zones.

The number of economically active household members positively influenced the adoption of the number of improved nursery practices adopted by tomato farmers. Years of schooling also had a positive relationship with the number of nursery practices adopted, thus additional year of school results in more nursery practices adopted by tomato farmers. Off-farm income positively and significantly influenced the number of nursery practices adopted by tomato farmers. Thus, farmers are able to channel income from off-farm activities to the adoption of more improved nursery practices and ultimately field tomato production. Farmers who own more plots are more likely to adopt more nursery practices. Farmers with a greater number of plots tend to have available land options for which they need to produce seedlings to cultivate such lands and are more inclined at adopting more improved nursery practices in order to ensure efficient nursery production and obtain the needed quantities of seedlings for cultivating the available plots.

The frequency of cultivation per year had a negative effect on the number of improved nursery practices adopted by tomato farmers, meaning farmers cultivating more cycles or times in a year tend to adopt very few improved nursery practices. Cultivating many times in a year implies spending more resources, including labor, capital and other inputs in the main cultivating hence having less resources and time to adopt more improved nursery practices.

Discussions

Our results reveal that tomato production is dominated by male farmers. This finding agrees who reported that the majority of African agricultural societies have families commonly headed by men. The high marital level of the tomato farmers from our findings implies that the farmers are generally from stable households and are able to explore available family labor for enhancing tomato production. This finding is similar to the study by Defoer (2003) who found that more of the African crop producers are married and live with their families to facilitate the production of their farm crops.

Willingness to adopt heat-tolerant tomato varieties

From our results, the key factors that influence farmers' willingness to adopt heat-tolerant tomato varieties include education, experience in tomato production, extension, and number of plots. Typically, farmers who have attained more years of formal schooling tend to be aware and better appreciate the importance and benefits of heat-tolerant varieties in reducing the impacts of climate variability and are more willingly to adopt such varieties. Similar studies have found a positive effect of education with the adoption of improved nursery practices on tomato production (Al-Shadiadeh et al., 2012; Frimpong et al., 2021; Akomdo et al., 2023).

The positive effect of experience implies that experienced farmers are able to confidently choose among varieties, with their experience tend to be more inclined to varieties that are tolerant to climatic variability and are more willing to adopt heat-tolerant tomato varieties. A strong association was found between experience and the adoption of pre-emergence tomato production practices among smallholder farmers in Ghana. Furthermore, experienced farmers tend to be more enthusiastic and willing to explore new things and are willing to adopt heat-tolerant varieties (Hassan and Nhemachena, 2008; Al-Shadiadeh et al., 2012; Martey et al., 2012).

The positive effect of extension on willingness to adopt heat-tolerant varieties implies that with increased visits by extension agents, farmers are able to receive extension advice, information, and technical support and also are able to participate in extension-related activities which enhance their willingness to adopt heat-tolerant varieties (Al-Shadiadeh et al., 2012; Akomdo et al., 2023). Smaller number of plots are a strategy adopted by smallholder tomato farmers for reducing the risk of crop losses from various sources such as climate variability, enhancing their likelihood of adopting heat-tolerant tomato varieties (Martey et al., 2012).

Adoption of improved nursery practices of tomato production

Major factor influencing the adoption of improved nursery practices included education, household size, and extension visits. Years of schooling showed a positive and significant relationship between fertilizer application, pruning, and hardening practices. This implies that as farmers attain more years of formal education, they tend to be more inclined toward adoption of improved nursery practice. This is because education enlightens the knowledge of the farmers, making them able to read, understand, and appreciate the benefits of adoption of improved nursery practices in order to obtain improved yields. Hence, educated farmers are able to decode and appropriately use improved nursery practices when introduced.

These findings correspond to similar studies (Al-Shadiadeh et al., 2012), indicating that the rate of adoption of a technology tends to be higher with the increasing level of formal education of a farmer. The involvement of a household member adds to the labor used in the farm in terms of these nursery practices to help performing these practices. Larger household size might benefit from being able to use labor resources at the right time and able to adopt more of the practices.

The negative effect of household size and fertilizer application and pruning from the results may be due to the fact that at the nursery stage, these two activities do not require substantial labor. Furthermore, these practices improve aeration and conservation of soil microorganisms, which increases the vigor of the seedlings and ultimately increase productivity of field production. In addition, the cultivation of more plots of tomato, as revealed in our findings, will require additional seedlings for planting, hence influencing the adoption of improved nursery practices. The results are similar to the study by Bezu et al. (2014) and Danso-Abbeam and Baiyegunhi (2017) who found a number of plots and farm sizes to positively influence the adoption of improved technologies.

Extension visits positively and significantly influenced the adoption of fertilizer application and hardening practices; thus, farmers are more likely to adopt these practices and other improved production practices through advice and guidance obtained from extension agents. Consistent with previous studies (Ayandiji and Adeniyi, 2011; Simtowe et al., 2016; Asante et al., 2017; Alhassan et al., 2018; Asante et al., 2021; extension has been found to positively influence the adoption of improved crop production technologies. Farmers are more likely to access to staking information and best staking times through FBO membership. Membership of a farmer association is positively associated with farm size decisions. Thus, tomato farmers belong to FBO benefits from training and other technical supports to enhance tomato production (Chebil et al., 2009; Asante et al., 2011; Kondo et al., 2020).

Increase in years of formal education enhanced the ability of farmers to appreciate the importance of improved nursery practices in enhancing tomato productivity in the field. In addition, farmers are able to appreciate the importance of these practices and better understand them during dissemination techniques by extension agents and other sources. The result are similar to the findings (Enrique and Eduardo, 2006; Alhassan et al., 2018; Baiyegunhi et al., 2019; Barnes et al., 2019; Kondo et al., 2020; Asante et al., 2021), where positive effects were found with education and adoption of improved technologies.

Number of nursery practices adopted by tomato farmers

Major factor influencing the adoption of number of improved nursery practices are number of economically active household members, years of schooling, off-farm income, and number of plots cultivated.

The positive effect of number of economically active persons on the adoption of improved nursery practices implies that an increase in the number of economically active persons in the household results in an increase in the number of improved practices adopted by the farmers. More economically, active household members imply the availability of additional labor or generate additional income to hire extra labor needed for adopting more additional nursery practices in tomato production.

Similarly, the positive effect of years of schooling on the number of nursery practices adopted is consistent with the study by Danso-Abbeam and Baiyegunhi (2017) who reported that longer years of schooling encourage the adoption of technologies among farmers. Furthermore, tomato farmers are able to take better production decisions with better ways of reducing cost (Martey et al., 2012; Asante et al., 2017).

Furthermore, our findings reveal that farmers with more plots are more likely to adopt more improved nursery practices. This finding is similar to the study by Wainaina et al. (2016) who found positive relations with number of plots and adoption of improved seeds and fertilizer in Kenya.

Conclusion and recommendation

This study examined the adoption of improved nursery practices and willingness to adopt heat-tolerant tomato varieties across three agroecological zones in Ghana. The results indicate that tomato production is dominated by men with mean age of 43 years, average of 7.5 years of schooling, and approximately 14 years of experience in tomato production. Most of tomato farmers involved in off-farm income generate activities with a typical household having approximately five members. However, the majority of tomato farmers are not members of farmer-based organization and innovation platforms. The results further indicate that years of schooling, sex, household size, off-farm income, number of plots, extension contacts, credit access, tomato experience, frequency of cultivation, FBO and IP membership, and being in the transition agroecological zone significantly and positively influenced the adoption of tomato nursery practices in Ghana. However, the absence of household head significantly and negatively influenced the adoption of tomato nursery practices.

To enhance the adoption of improved heat-tolerant tomato varieties, the increasing climatic variability will require pragmatic efforts toward improving access to these factors. This should include facilitating access to credit, training through workshop and seminars, and strengthening access to extension services, farmer-based organizations, and innovation platforms. Furthermore, there is a need for stakeholders, especially MoFA, to upscale extension services and strengthen FBOs and IPs among tomato farmers across agroecological zones, to improve the adoption of heat-tolerant tomato varieties in Ghana. In addition, collaboration with local government authorities to facilitate group formation among tomato farmers and guiding and assisting them to identify competitive markets with better bargaining needs to be promoted.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://drive.google.com/file/d/1VE5-YGruEv_JpJAI3VT5JSmfZzSnp8Y4/view?usp=share_link.

Ethics statement

The requirement of ethical approval was waived by the Faculty of Agriculture Review Committee for the studies involving humans because Faculty of Agriculture Review Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) and minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

Author contributions

BOA: Writing – original draft, Methodology, Formal analysis, Conceptualization. MO: Writing – review & editing, Supervision, Project administration, Funding acquisition. KB: Writing – review & editing, Resources. BA: Writing – review & editing, Conceptualization. JG: Writing – review & editing, Investigation, Conceptualization. JA: Writing – review & editing. RP: Writing – review & editing.

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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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Reducing vulnerability to climate change among millet and sorghum farmers in Ghana: interrogating the contribution of climate-smart agriculture in northwestern Ghana

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Reducing vulnerability of smallholder farmers to climate change is a global issue. One approach viewed as important in reducing farmers' vulnerability to climate change is Climate-Smart Agriculture (CSA). CSA is often seen as an approach to redefine, reposition and sustainably manage agriculture. Given the importance of CSA practices in sustaining the food needs of many farm households in sub-Saharan Africa and Ghana, this study investigates CSA practices that were introduced to farmers by Center for Indigenous Knowledge and Development (CIKOD), interrogates the contributions of CSA to reducing farmers vulnerability to climate change and established the relationship between CSA and climate change adaptation. The study employed a mixed method approach, using 146 smallholder millet and sorghum farmers. Questionnaire and interviews were used to generate primary data for analysis. Descriptive statistics, involving Chi-square test and relative importance index were used to analyze the questionnaire while thematic analytical approach was used to analyze the interviews. The results of the study revealed that CSA practices such as crop rotation, weed control, contour farming, and land rotation are deployed by smallholder farmers to respond to drought, dry spell and flood in the Municipality. Asset holding capacity, credit, access to climate information, and extension services were found to be key determinants of farmers' adoption of CSA practices. The study recommends the need for the Ministry of Food and Agriculture to provide some technical support to smallholder farmers to successfully adopt these practices for sustainable farming. Again, the study recommends the need for non-governmental organizations and development partners, which over the years have shown interest in promoting CSA practices among farmers, to continuous to support and promote the adoption of CSA by farmers.

KEYWORDS

climate-smart agriculture, climate vulnerability, cereal crop, climate change, food security

1 Introduction

The global population is projected to increase to around 8.5 billion in 2030, 9.7 billion in 2050 and 10.4 billion in 2100 (FAO, 2022; Petrakis et al., 2023). This projected increase in population numbers will imply that agriculture must be at its best to meet the food needs of the growing population. With agricultural productivity projected to decline by 17–28% in sub-Saharan Africa due to farming systems' sensitivity and vulnerability to volatile climatic conditions, poor agricultural households will suffer to meet their household food demand (Sakho-Jimbira and Hathie, 2020). Studies have observed that sub-Saharan Africa is highly sensitive and more vulnerable to climate change and suggest the need to improve their agricultural production systems to tackle the threats of climate change and other weather uncertainties (Pereira, 2017; File and Derbile, 2020; Owusu et al., 2021). No doubt, climate change has become a critical development challenge and net threat to achieving sustainable development. Given the importance of agriculture in meeting the current and future food needs of the global population, investment, and adoption of agricultural technologies need to be considered.

In recent years, there has been serious advocacy for sustainable agriculture. The call for sustainable agriculture is to improve agricultural productivity and incomes of farmers while managing the emission of greenhouse gasses into the atmosphere (FAO, 2013; Zougmoré et al., 2016; Anuga et al., 2019; Zakaria et al., 2020; Autio et al., 2021). One approach that appears dominant in the call for resilience and sustainable agriculture is climate-smart agricultural practices. Climate-smart agriculture is an approach that seeks to: (1) increase agriculture productivity in a sustainable manner, (2) improve the resilience of agricultural production and food systems to climate change and (3) reduce net greenhouse gas emissions associated with agriculture and forestry sectors (FAO, 2013; Yiridomoh, 2021). According to the Rainforest Alliance et al. (2024), CSA is an approach that combines different methods to increase agricultural food production under a climate change umbrella. The promotion of climate-smart agriculture is observed to enhance agricultural productivity and increase the resilience of farming systems against climate change (FAO, 2013; Zakaria et al., 2020; Azadi et al., 2021). Globally, studies have recognized the criticality of climate smart agriculture to sustainable agriculture and food security (Zougmoré et al., 2016; Azadi et al., 2021). Attention in the development, promotion, and adoption of climate-smart agricultural practices has always targeted at least developed regions, especially sub-Saharan Africa due to the region's sensitivity and vulnerability to climate change.

The latest Intergovernmental Panel on Climate Change report shows that sub-Saharan Africa (SSA) will continue to experience decline in grain yields due to climate change (Ayanlade et al., 2023). Studies specifically on climate-crop modeling suggest that activities of agriculture will be disproportionately affected in SSA (Owusu and Yiridomoh, 2021; Derbile et al., 2022). Given that majority of the people depend on agriculture for their livelihood, agricultural vulnerability to climate change is of great interest to policy makers, academics and other development partners. The decision for climate change adaptation as a global public goal is enshrined in the Paris Agreement (Article 7). The question for many sub-Saharan countries is when and how to act and which adaptive strategies to pursue to reduce the fragility of agricultural systems for sustainable food production. This is because without sustainable and appropriate farm-level responses and interventions, climate change will likely affect agricultural yields and food security, and increase poverty levels in SSA. Earlier studies have observed that CSA technologies must be introduced to farm households in Africa and other developing economies (Alexander, 2019; Mashi et al., 2022; Njogu et al., 2024). Accordingly, the introduction of climate smart-agricultural practices to smallholder farmers has the propensity to support sustainable agriculture through improved agricultural productivity, income, and food security. However, despite the call for the implementation and promotion of CSA in sub-Saharan Africa, the specific role CSA plays in sustaining grains cultivation (specifically millet and sorghum) in Ghana is limited and least investigated.

Just as in Ghana and in other parts of Africa, millet and sorghum are important crops that are cultivated all over the world particularly, Asia and America. In Ghana, the farming of millet and sorghum are closely associated with the indigenous culture over centuries. Millet and sorghum have been mixed cropped for centuries and are nutritionally preferred to others cereals such as barley, wheat, rice and maize. According to Prasad and Staggenborg (2009), the two crops contain high levels of calcium, iron, fiber, and relatively lower energy content, which make them ideal for weaning children. Local knowledge shows that the two crops form the staple diet of major communities within the northern and other parts of Ghana where they are used to make local dishes such as *Tuo Zaafi* (TZ), *fura,* and *zoom* (kom) (Agyakinla, 2018). Despite the significant role of millet and sorghum in household food security, climate change is observed to impact the yield of these two crops. As observed by Derbile et al. (2022), the yield of the two crops has been declining since 1990. This has plunged the area cropped of millet and sorghum to 3rd and 4th places among the most cropped food plants in Ghana [Ministry of Food and Agriculture (Ministry of Food and Agriculture, 2010)] and overtaken by other cereals like maize and rice.

Situated in North-western Ghana, the Lawra Municipality is one of the municipalities in the Upper West Region where millet and sorghum are predominantly cultivated for food and the cultural needs of the people. In fact, they are the first choice crops that are cultivated within the municipality, and almost all farm households within the municipality cultivate the two crops for their food security needs and traditional rites (Ministry of Food and Agriculture, 2010; Seglah et al., 2022). In recent years, development partners, including the Center for Indigenous Knowledge and Development (CIKOD), have introduced smallholder farmers to climate-smart agricultural technologies in the municipality for sustainable farming. Previous studies have given attention to factors that influence farmers' adoption decision to CSA practices. However, how adoption of these CSA practices has supported farmers to adapt to climate change especially in resource-scare location of Ghana is least interrogated. Thus, this study seeks to answer the following questions: (1) What are the climate-smart agricultural practices introduced to farmers? (2) What are the contributions of the introduced CSA technologies for farm-level adaptation? (3) What are the associations between CSA practices and climate change adaptation? Providing answers to these questions do not just contribute to critical literature on CSA adoption but also provide a framework for understanding the nexus between CSA and climate change adaptation in resource scarce setting in north western Ghana. The rest of the paper is organized as follows: the succeeding sections consist of the conceptual framework, the methodology, results and the discussions of the study.

1.1 Climate-smart agriculture and climate vulnerability reduction of farmers

Climate vulnerability has become important in climate change research globally. Vulnerability studies are key to define systems exposure and sensitivity to climate change for systems adaptation decisions. Often viewed as a contested concept, vulnerability is when people are prone to future acute loss in capacity to respond to climate-induced disasters. In other words, vulnerability is the tendency to be adversely affected by actions and inactions of climate change. Climate vulnerability is widely known to differ within communities and across societies, regions and countries, and also through time (Ayanlade et al., 2023). Agriculture in Africa and other developing economies are observed to be vulnerable to global and local climate change. The agricultural sector vulnerability to climate change in Africa, in particularly, is due to the sector's high reliance on rainfall for its activities (Wekesa et al., 2019; Yiridomoh et al,. 2020). Studies across Africa and the globe observed food crop yields reduction in the coming years due to low adaptive capacity of farmers to climate change (Eggen et al., 2019; Sultan et al., 2020; Ayanlade et al., 2023). Using a large ensemble of historical climate stimulations derived from an atmospheric general circulation model and two process-based models (SARRA-H and CYGMA) to assess climate effects on crop production in West Africa, Sultan et al. (2020) observed that climatic conditions have caused regional average yield reductions of 10–20% for millet and 5–15% for sorghum in the two models. Using a participatory approach to assess sources of vulnerability of farmers to climate change in Zimbabwe, Rurinda et al. (2014), found that food crops of farmers have been affected by multiple stress factors such as soil degradation, water deficit and limited rainfall caused by climate change.

Climate change and agriculture will continue to interact with the former setting the development pace for the latter. This implies that developing and implementing emerging agricultural technologies is core to agricultural development. Over the years, climate-smart agriculture has been seen as an approach to support farm households respond to climate. The approach is premised on three pillars; increase yields of farmers through adaptation, improve income of farmers and assist in mitigating climate change through reduction in greenhouse gasses. Climate-smart agriculture, over the years has been observed to reduce farmers' exposure and vulnerability to climate change through improved yields of farm activities. For instance, Tesfaye A. et al. (2021) study in Ethiopia on climate-smart innovations and rural poverty reported that climate-smart technologies such as cereal-legume intercropping, minimum tillage and their combination (cereal-legume plus minimum tillage) have helped reduce the incidence and depth of poverty of smallholder farmers. Sarr et al. (2021) study on who benefits from climate-friendly agriculture in Tanzania found that intensification of rice system significantly contributed to improved rice yield. In Ghana, Issahaku and Abdulai (2019) reported that climate-smart innovations such as water and soil conservation and crop choices has resulted in reduction in multi-dimensional poverty and downside risk exposure of farmers to climate and environmental change. The study further observed that adopting climate-smart agricultural practices positively and significantly impacts food and nutritional security.

Martey et al. (2020) study on climate-smart innovations on food security reported that adopting row planting and drought-tolerant maize varieties increased crop yield and intensity of maize commercialization. Shahzad et al. (2021) on climate-smart agricultural practices in Pakistan, revealed that climate-smart technologies such as cropping calendars, diversified seed varieties, changing input mix and soil, and water conservation measures significantly improve household food security and enhance household dietary diversity. Other studies have also reported on yield and income effects of climate-mart agricultural innovations (Miller et al., 2021; Bazzana et al., 2022; Li et al., 2022; Yamoah and Kaba, 2022; Ali et al., 2023). Li et al. (2022) study on climate-smart innovations and crop yield in China found that farmers who adopted CSAs have seen their rice yield increase. No doubt, climate-smart agricultural practices could play a significant role in reducing climate-related vulnerabilities of farmers if they are properly introduced to these technologies. This therefore suggests that building the synergies between indigenous knowledge systems and climate-smart agricultural technologies could proffer successful climate adaptation solutions to farmers.

1.2 Conceptual framework of the study

As indicated by the sustainable farming framework (SFF), climate change is a threat to the agricultural sector. Rising temperatures, declining rainfall, and rising sea levels are observed to impact activities of farming. As already reported by previous studies, the impact of climate change has grave implications on the agricultural sector because of the sector's high dependence on rainfall for its activities (Yiridomoh et al., 2021; Belford et al., 2023; Mehraj et al., 2023). As typified by the framework, climate change will determine agricultural potential and its impact will determine whether millet, sorghum and other crops will survive the test of climate change. As reported by earlier studies, the adverse impact of climate change will affect all sustainable farming practices, with consequent effects on food availability, accessibility, stability, and utilization (Owusu and Yiridomoh, 2021; Yiridomoh et al., 2021; Ayanlade et al., 2023). Thus, increasing weather extremes as noted by the framework (see Figure 1), will force many vulnerable households into food insecurity due to exposure of food production systems to climate change. In some cases, household vulnerability may result in maladaptation due to severe impact of climate change on farm activities.

Sustainable farming as depicted by the framework depends heavily on climate-smart agricultural technology adoption. Thus, reducing vulnerability of farmers to climate change will imply that they are introduced to climate-compatible agricultural activities such as land, soil and water management practices. Studies have indicated the need to provide strategies to enlarge potential crop production through expanding rain-fed and irrigated agricultural areas (Antwi-Agyei et al., 2021; Owusu and Yiridomoh, 2021; File et al., 2023). No doubt, there exists extant literature on smallholder farmers' vulnerability to climate change through frequent crop failures, reduced cropping areas due to climate extremes such as droughts and floods, especially in developing countries. Sustainable farming through adoption of climate-compatible farming practices is a must to protect smallholder farmers against harsh climatic conditions. Climate-smart agriculture supports farmers' farm decisions for sustainable farming as exemplified by Figure 1. The opportunities for adoption of climate-smart agricultural activities are to reverse the impact of climate change on farming activities. As reported by studies,

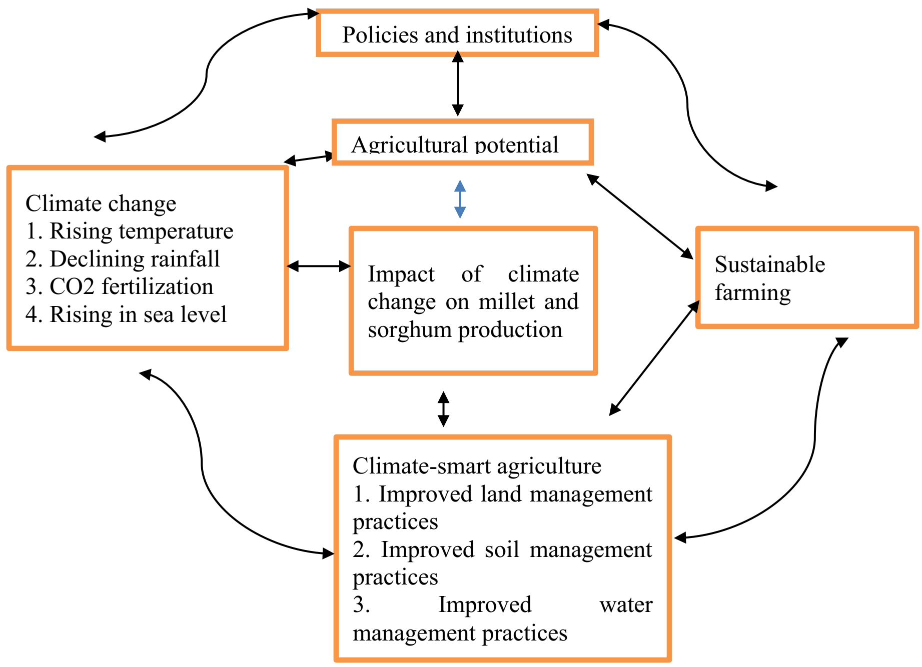

FIGURE 1
Sustainable farming framework. Source: Authors constructs, 2023.

adoption of climate smart agriculture is to enhance farmers' capacity for climate change vulnerability reduction through adaptation (Makate et al., 2019; Jamil et al., 2021; Nyang'au et al., 2021).

Climate-smart technologies' adoption requires government policy intervention which sometimes could be complex public planned adaptation projects to include weather prediction, irrigation for water conservation, sustainable soil management, introduction of improved crop varieties and livestock management. The effectiveness of public policies and institutions in climate-smart agricultural technologies adoption will have positive implication on sustainable and future farming. This implies that for farmers to appropriately adopt climate-smart agricultural technologies for sustainable farming, public institutions and their policies must be tailored toward smallholder farmers to support the climate adaptation behavior. As reported by studies, how and when climate-smart technologies are used by farmers is dependent on how these policies are developed and implemented by institutions (Totin et al., 2018; Makate et al., 2019; Tanti et al., 2022). Strong public policies and institutions are prerequisite requirements for the adoption of climate-smart agricultural technologies and have consequential effects on sustainable farming.

2 Materials and methods

2.1 Study location

The Lawra Municipality is one of 11 Districts in the Upper West Region of Ghana. The municipality is bounded to the east by the Lambussie-Karni district and to the west and south-west by the Republic of Burkina Faso and located within the Guinea Savanna vegetation zone of Ghana (see Figure 2). The guinea Savanna zone is characterized by scattered woody trees, which are usually short in height. The area is known for its short grasses except areas along the Black Volta River where the grasses are taller. Most of the trees in the municipality are drought and fire resistant, making them more resilient to climate and environmental changes. For instance, baobab, dawadawa, shea, and acacia are the most common trees in area, and these are highly resistant to drought and wild fires. These trees are of economic importance to the sustenance of the residents in the municipality as they provide extra income to farm households, especially women.

One annual environmental challenge of the area is drought, which usually starts from early October and runs through to early April. When the drought occurs, the grasses become dry and get burnt subsequently. This usually leaves the area very patchy and bare. The early torrential rains which are unpredictable these years also set in around April and May. These are the months in which farmers start to clear their lands for activities of farming. Due to the erratic nature of the rainfall, farming and other agricultural activities are affected, resulting in low agricultural yields as farmers depend mostly on rain-fed agriculture. The climate of the municipality is the tropical continental type. This is characterized by mean annual temperature ranging between 27 and 36°C. February to April is the hottest period in the municipality and the region at large, while April to October is the period in which the municipality receives rainfall, which usually is the wet and farming season.

2.2 Study design

Based on the paradigm of pragmatism (Johnson et al., 2007), which focuses on research outcomes and allows researchers freedom in the choice of methods that best meet their needs, an exploratory sequential mixed-methods research design was adopted for the study.

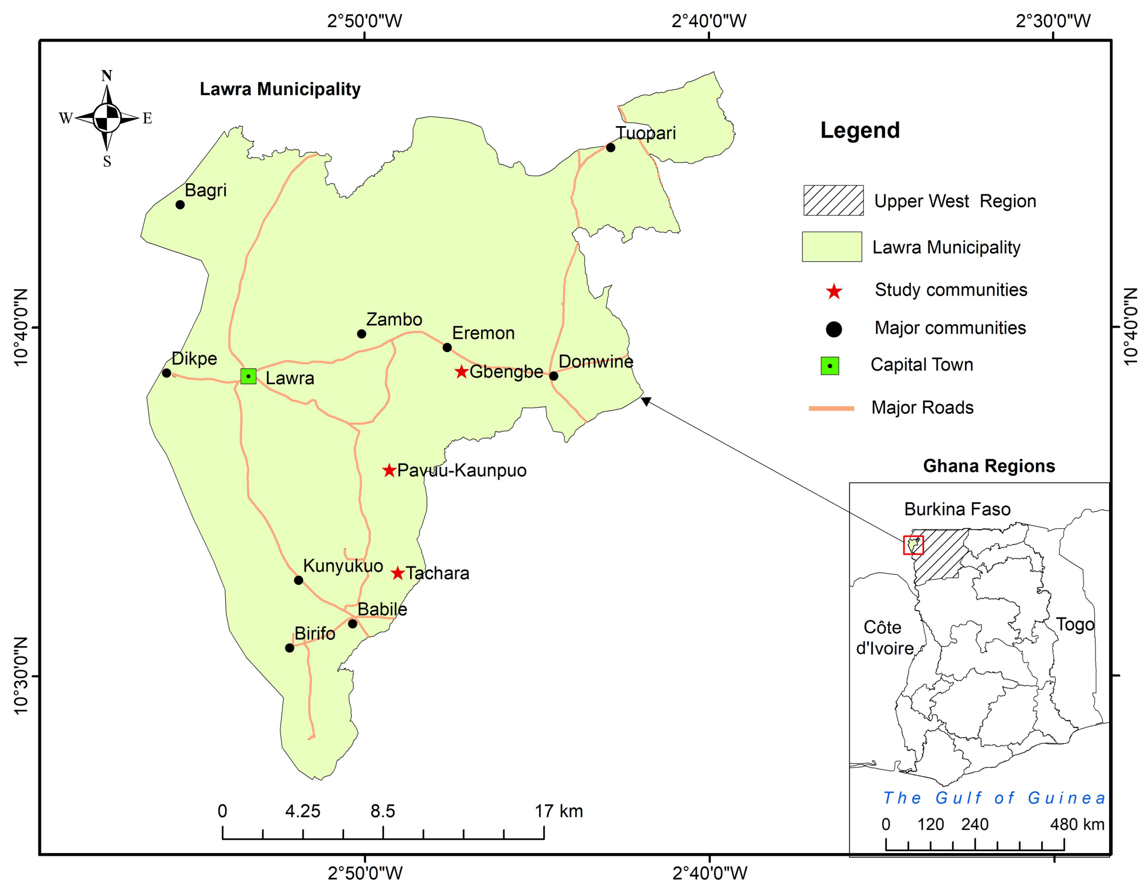

FIGURE 2
Map of Lawra municipality showing the study communities.

An exploratory sequential design involves a study in which the qualitative dimension (data collection and analysis) of the study is conducted first followed by the quantitative data collection and analysis (Fetters et al., 2013). The interest in the exploratory sequential mixed methods approach is to present more balanced findings that would be relevant for agricultural sector climate change adaptation planning.

2.3 Population and sample

The study was conducted among smallholder farmers in 12 communities within the Lawra Municipality who were introduced to climate-smart agriculture by the Center for Indigenous Knowledge and Organizational Development (CIKOD) in 2014. The communities are Tanchara, Tanchara Saazu, Kporo, Daboziire, Dawna, Gbelinkaa, Pavuu-Kaungpuo, Tiakoni, Danllar, Gangduor, Gbengbe, and Dobozirre. A purposive and simple random sampling techniques were used to select the municipality and the communities, respectively. The Municipality was purposely selected because of its introduction to climate-smart-agricultural practices, high poverty indices and its vulnerability to climate change. Thus, the purposive sampling approach was used to select the Lawra municipality and simple random sampling was used to select three communities out of the 12 for the study. By way of applying the simple random approach, all the 12 communities that were introduced to the CSA practices names were interdependently written on pieces of papers, gently folded and put into a container for the three communities to be drawn among the folded list of communities. Simple random sampling technique was again employed to recruit the individual farmers for the study. Simple random is suitably used when the population under study has homogenous characteristics. In this study, the researchers deployed the simple random sampling by first assigning consecutive numbers from 1 to n, next to each farmer in each community under study (i.e., n = population of farmers in each community). Second, a list of random numbers with the help of random number table which was manually developed enable the researchers select the number of farmers in each community from the total list of farmers of that community (see Figure 3).

For the selection of the sample size for the study, a proportionate sampling approach guided by data collected from CIKOD (see Figure 3) was used. Using the Yamane (1967), formula: $n = \frac{N}{1} + N_e^2$, where n = sample size; N = sample frame, and e = disturbance term, which was (0.05), a sample size of 146 millet and sorghum farmers was used for the study.

2.4 Data collection instruments

Two data collection instruments were used; in-depth interviews and structured questionnaire. In-depth interviews were conducted

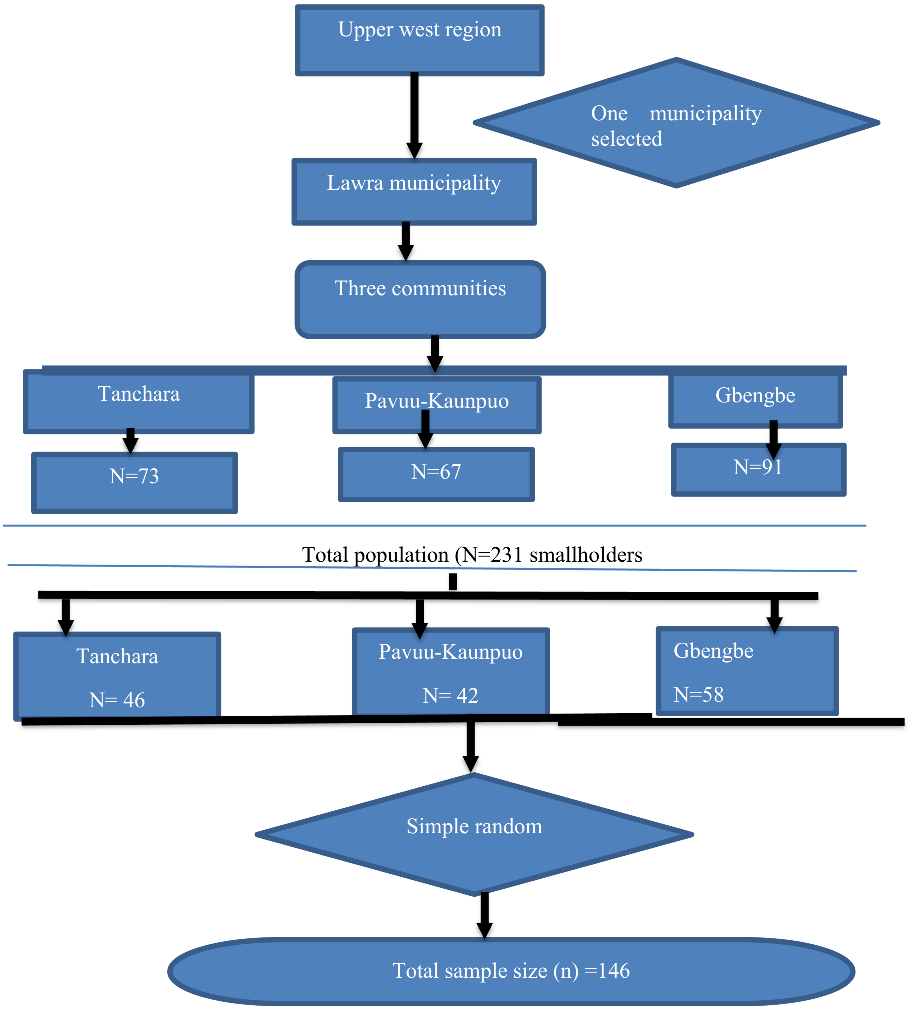

FIGURE 3
Sample construction. Source: author's construct.

with climate-smart champions in all the three communities in the municipality. Climate-smart champions are millet and sorghum farmers recognized by their peer farmers as real adopters of climate-smart agricultural practices. The interview with the climate-smart champions was face-face interaction between the researchers and the individual respondents (Climate-smart champions). The adoption of the face-face approach is because it offers a greater degree of flexibility. It provides an avenue where answers are probed by the researcher and clarification made where necessary by the respondent on questions for better comprehension before answering. The climate-smart champions were identified with the help of farmers during the questionnaire administration. A follow up was made on the names mentioned to the research team and interviews were conducted with them too. It was the intention of the study to conduct 15 interviews with the climate-smart champions, however, after 12 interviews (see Table 1), data saturation was reached and the interviews were stopped. All the interviews, which usually lasted for 30–45 min, were conducted with farmers at their homes.

Just like the in-depth interviews, the structured questionnaire was granted to millet and sorghum smallholder farmers on their perspectives of climate-smart agriculture, the kind of climate smart technologies adopted by farmers and their contributions to climate change vulnerability reduction among the smallholder farmers. The structured questionnaires were administered to millet and sorghum farmers in their homes, with each questionnaire lasting for 40 min. For relevance and accuracy of the questionnaire to the success of the study, a pilot study was conducted in Babile, one of the communities in the Municipality. That procedure involved administering the developed questionnaire to millet and sorghum farmers and then following up to get responses on the questions on how they are structured, and whether they were understood by the respondents and felt comfortable responding to them.

Before the study was conducted, all the participating communities' consent was sought, and respondents' confidentiality was assured. Where audio recordings were done, participants consent were asked and confidentiality in the management and use of the recorded audios was clearly assured.

2.5 Data analysis

The quantitative data was analyzed using descriptive statistics such as frequencies and percentages. The descriptive statistics was analyzed using Statistical Package for Social Scientists (SPSS Version 21). To determine the relationship between CSA and climate vulnerability reduction, a chi-square test (Greenwood and Nikulin, 1996) was performed to examine CSA practices that are significantly associated with climate risk reduction. To identify CSA practices that were perceived effective and of importance to the farmers over others, a Relative Importance index (RII) analysis was conducted. Farmers were asked to score the relative importance of the different CSA practices using a four-point rating scale (high, medium, low and no). The relative importance index was calculated based on the following index formula $RII = RI_n + 0 + RI_I \times 1 + RI_m \times 2 + RI_h \times 3 \ldots$ (2) Where; RII = Relative Importance Index, RI_n = frequency of farmers rating CSA practice as not important, RI_i = frequency of farmers rating CSA practice as less important RI_m = frequency of farmers rating CSA practice as moderately important RI_h = frequency of farmers rating CSA practice as highly important (Uddin et al., 2014). For the qualitative data, thematic approach was used (Attride-Stirling, 2001). Thus, all interviews were transcribed by the first author and shared the transcripts with the other two authors for codes and themes identification. The transcripts were independently read by the three authors to identify the codes and themes for analysis. The individual researcher's read of the transcripts helped the authors identify themes relevant to make a case for the contribution of CSA for climate vulnerability reduction. The themes identified were used to support the descriptive statistics to present a more balanced results of the study.

3 Results

3.1 Demographic characteristics of respondents

The study presents the demographic characteristics of the millet and sorghum farmers in the Lawra Municipality (see Table 2). From the analysis, 83% of the respondents were male while 17% were female. The male dominance in the production of the millet and sorghum, according to the study, is because these crop varieties are considered as traditional crops and usually cultivated for cultural and traditional purposes, in which women have limited roles. Again, the demographic analysis, revealed that 81% of the respondents were married, 13% were widows while 5 % of them were divorcees.

On production goal or purpose of engaging in millet and sorghum farming, 96% of the respondents indicated the production was for home consumption while three and 1 % indicated that production of sorghum and millet is for commercial and for both commercial and household consumption, respectively. Further analysis of the demographic information of the respondents indicated that, 88% of the farmers received farming information from NGOs, while 8 and 3% of the respondents indicated that they received farming climate information through the Ministry of Food and Agriculture and its subsidiary units.

3.2 Perceived effects of climate-induced variables on yield of millet and sorghum in the Lawra municipality

The perceived effects of climate-induced variables on the yield of millet and sorghum in the Municipality are presented (see Table 3). As indicated by the Table 3, various climate-induced derivatives were explored and farmers were asked if they had any effect on their sorghum and millet production. The responses of the participants revealed that drought, dry spells, windstorms, bushfires and floods had great implications on their millet and sorghum production. Specifically, 80% of the respondents observed that over the years floods had increased with grave consequences on their food crop production.

TABLE 1 List of interview participants.

Community	Climate-smart champion (CSC)	Sex	Pseudonym
Tanchara	CSC 1	M	A1
	CSC 2	M	A2
	CSC 3	M	A3
	CSC4	M	A4
	CSC5	F	A5
Pavuu-Kaunpuo	CSC 1	M	B1
	CSC 2	M	B2
	CSC 3	M	B3
	CSC 4	F	B4
	CSC5	F	B5
Gbengbe	CSC 1	F	C1
	CSC 2	M	C2
	CSC 3	M	C3
	CSC4	M	C4
	CSC5	F	C5

TABLE 2 Demographic characteristics of respondents.

Characteristics	Frequency	Percentage (%)
Gender		
Male	121	83
Female	25	17
Total	146	100
Marital status		
Single	2	1
Married	119	81
Widowed	19	13
Divorced	6	5
Total	146	100
Farming purpose		
Household consumption	140	96
Commercial	5	3
Both	1	1
Total	146	100
Source of information for farming		
MOFA/AEAs	11	8
Radio	4	3
Television	1	1
NGOs	130	88
Total	146	

Source: Study's field survey, 2023.

Millet and sorghum farmers also observed that rainfall over the years had been sporadic, however, they noted that any time they experienced heavy rainfall, their valleys and farm lands get flooded, with adverse consequences on the development of the sorghum and millet as captured by A1:

> *"Flooding has been part of our existence here. We have been experiencing flooding since time immemorial. However, in recent years, the flooding is devastating with adverse consequences on those of us who cultivate millet and sorghum. The worst affected are those who have their farm lands located along rivers and streams."*

On farmers' responses to drought, respondents observed that drought has been rampant in the past decade causing farmers' crops to wilt and dry up. Just like drought, farmers also mentioned dry spells, which are as devastating as the drought itself. As indicated by Table 3, 100 and 92% of the respondents indicated that drought and dry spells, respectively, were intense with dire repercussions on the yield of sorghum and millet. Farmers mentioned annual drought and dry spells especially around June–August where farmers expect rains for their farming activities. According to the farmers, due to limited rains experienced annually, bush fires set in quickly usually around October and November, and consume their crops. The farmers indicated that, sorghum and millet take 4–5 months to mature and are ready for harvest usually around October and November, but grasses and bushes get dried around the same period, and any bush fires around that period will cover a wide area, usually with sorghum and millet farms suffering the consequences.

Aside these climate-induced variables, windstorms were observed by the farmers to negatively impact millet and sorghum. According to the farmers, due to the height of the two crops, anytime there is windstorms precipitated by rainfall, most of the crops fall to the ground, and consequently, are unable to produce good grains.

3.3 Climate-smart agricultural technologies adopted

The study presents the climate-smart agricultural technologies adopted by the millet and sorghum farmers (see Table 4). As indicated by Table 4, 21% of the farmers used land rotation/fallowing as a response strategy to climate change. Again, the results indicated that 13% each of the farmers used early weeding for weeds control and transplanting of crops to respond to the changing climate system. The results further revealed that 18 and 11% of the respondents adopted to crop rotation and contour farming respectively, which support them reduce their vulnerability to climate change. The results also indicated that 7, 6, and 5% adopted agro-forestry, manure application, and erosion control by bunding, respectively, as climate-smart strategies to respond to climate change. The interview with the climate-smart champions revealed that land rotation or fallowing has been with them since time immemorial and has been playing a significant role in the climate change adaptation processes. According to the interviewees, fallowing or land rotation

TABLE 3 Perceived effects of climate-induced variables on farms.

Statement	5-highly increased	4-slightly increased	3-unchanged	2-slightly decreased	1-highly decreased
Farmers' perceived effect of on-farm flooding on yield of millet and sorghum	87 (60%)	29 (20%)	19 (13%)	7 (5%)	4 (2%)
Farmers' perceived effect of changes in frequency of rainstorms on yield of millet and sorghum	86 (59%)	19 (13%)	27 (12%)	9 (6%)	5 (3%)
Farmers' perceived changes in frequency of dry spells on yield of millet and sorghum	103 (71%)	31 (21%)	12 (8%)	–	–
Farmers' perceived effect of drought on yield of sorghum and millet	139 (95%)	9 (5%)	1 (%)	–	–
Farmers' perceived effect of changes in frequency of bush fires on yield of millet and sorghum	121 (83%)	13 (9%)	12 (8%)	–	–

TABLE 4 Climate-smart agricultural practices adopted by millet and sorghum farmers.

Variable	Frequency	%
Land rotation/fallowing	31	21
Transplanting	18	12
Erosion control with verte vega grasses	5	3
Crop rotation	23	17
Manure application	9	6
Agro-forestry	11	8
Erosion control by bunding	7	5
Monocropping	5	3
Contour farming	16	11
Early weeding	21	14
Total	146	100

involves continuously allowing the land to freely lie for few years uncropped. The respondents mentioned that, land rotation has been noted among them as a smart strategy to respond to climate and environmental change which are now more pronounced in recent years as captured by C4:

> *Today, we are facing the reality of climate change. Our lands were not infertile years ago. We did the land rotation those days but not as frequently as we do today. Today, the frequent rotation of land is necessary to allow the land to possibly regain its lost fertility for crop farming. That has been a smart strategy majority of the farmers in this locality are adopting to respond to climate/environmental change.*

The interview with the climate-smart champions further revealed that crop rotation, using leguminous crops assists farmers to sustainably manage soil fertility for millet and sorghum production. According to the farmers, leguminous crops such as soya beans, bambara beans, groundnuts and beans are rotated with millet and sorghum on yearly basis so that the later crops can benefit from nitrogen which is fixed into the soil by the former crops. The interviewees indicated that, just like land rotation, crop rotation has been with them for ages and has been very influential in their farm decision-making. Accordingly, crop rotation has aided them reduce soil susceptibility to climate and environmental change. Respondents framed crop rotation as a smart strategy to respond to soil degradation, caused by the changing climate system as captured by A3:

> *Crop rotation is as old as this community itself. However, it has now become more important to all farmers in this locality because of continuous loss of soil fertility. We do the crop rotation as a strategy to maintain soil fertility through the atmospheric nitrogen which is fixed into the soil by the leguminous crops, which are used by the millet and sorghum.*

As indicated in Table 4, one of the climate-smart approaches farmers use to reduce vulnerability to crop failure is transplanting. According to the farmers, transplanting of crops is an indigenous smart way of responding to drought and dry spells which usually cause their crops to dry up. To do this, farmers broadcast the millet and sorghum seeds under a shade of a tree inside their farms to germinate. These are later transplanted to fill the spaces of the planted seeds that died due to drought or a dry spell. According to the farmers, under the shade of trees, the millet and sorghum seeds are able to withstand the drought and are then transplanted during the peak of the rains in either an open field or in the spaces left by the drying up of originally planted crops (see Figure 4). Because farmers, nurse the seedlings under trees, in times of extreme water stress, they are able to irrigate the crops without wasting water. This practice according to farmers helps them increase yields because a shorter season naturally leads to the late variety's failure at worst or low yield; with this strategy they are able to crop them.

The study again found that farmers used mono-cropping as a smart approach to increase crop yield. According to the farmers, mono cropping helps increase plant population and reduce the density of different crops competition for soil nutrients and water. To implement this, farmers indicated that, lands for millet and sorghum are solely dedicated for that and no crop is intercropped or interjected on same piece of land. Farmers acknowledge the risk involved in mono cropping as the entire farm containing the millet or sorghum may collapse. However, they indicated that they have other farms where they do the intercropping, citing maize and groundnuts, and yam and beans.

One other dominant farming practice that was reported by the study was contour farming (see Figure 5). The contour farming involves raising mounds around the base of the millet or sorghum crop during the peak of the season using a hoe, a practice which

FIGURE 4
Newly transplanted sorghum on farm plot.

FIGURE 5
Contour farming/terracing done to ensure water percolation.

TABLE 5 Ranking the relative importance of CSA practices.

Variable	High	Medium	Low	No	ASI	Rank
Early weeding	141	5	0	0	433	1
Land rotation/fallowing	89	31	23	3	355	2
Crop rotation	81	36	22	7	345	3
Manure application	82	33	17	14	343	4
Agro-forestry	77	28	29	12	328	5
Contour plowing	67	39	25	15	319	6
Transplanting	46	57	36	7	295	7
Monocropping	37	45	52	12	265	8
Erosion control by bunding	21	59	60	6	247	9
Erosion control with verte grasses	37	21	19	69	241	10

is believed to increase fertility in the following season while creating runways for water passage during flooding of the field. According to the farmers, the contour farming plays several functions including; erosion control, supporting the base of the crops from falling down during windstorms and also improving the moisture content of the soil (see Figure 5).

Agro-forestry, as a CSA approach, was found to be used by farmers in response to climate change in the municipality. According to the farmers, trees such as mango, acacia, baobab, shea trees and neem are integrated into farm plots. According to the farmers, the agroforestry approach helps them find a balance in raising food crops and forest management. For the farmers, the adoption of agroforestry has the potential to increase the capacity of seasonal crops to tolerate drought and thus enhance farmer's food security by avoiding total failure on the farm as captured by C1:

> *"Agroforestry is an approach we have been using all these years. We do not cut down the economic trees we find on our farm plots. Mango, shea, dawadawa, baobab* etc. *are trees we reserve on our farm plots. Besides the economic value for their reservation, these trees help increase the amount of organic matter in the soil through the dropping of the leaves onto the soil."*

3.4 Climate-smart agricultural practices and their relative importance

To determine the relative importance of CSA practices, a Relative Importance Index (RII) was performed. The results in Table 5 indicated that early weeding of farm plots by farmers was ranked as the most important CSA practice with a rank score of 433. Land rotation/fallowing and crop rotation were ranked second and third with rank scores of 355 and 345, respectively. CSA practices that were ranked as least important by the farmers were erosion control, monocropping and transplanting. Weeds control is critical to farm management as weeds compete with crops for nutrients and space. Just like the weed control, land rotation or fallowing plays a great role in soil and land management as the practice helps the soil to regain it fertility for crop growth and development.

3.5 Contributions of CSA practices in reducing climate change vulnerability of millet and sorghum farmers

On the contributions of CSA practices to climate change vulnerability, the results indicate that CSA has been playing critical support to farmers' vulnerability reduction. As shown by Table 5, CSA has been supporting farmers to addresses challenges of climate variables including; drought, floods windstorms. As shown in Table 6, drought has been one of the climate variables that determine household food security and vulnerability through drying of crops of farmers and loss of soil moisture, making it highly difficult for farmers to meet the food needs of their families.

However, farmers' adoption of CSA practices such as nursing and transplanting and terracing and contour farming has minimized their exposure to drought and its effects on farm yield. According to the farmers, nursing and transplanting of crops has helped them adjust their farming to meet the effects of erratic rainfall. Nursing and transplanting have helped them improve their crop yield through improvement in the density of crops on the farm plots., Nursing and transplanting of crops over the years has also aided them to get enough yield to take care of their households amidst climate change as captured by B2:

> *"Nursing and transplanting have been with us since time immemorial, and has been good in supporting farmers respond to drought every year. Initially, I was not practicing it because my crops never failed me. However, in recent times, due to persistent drought and its resultant effects on plant germination, the approach has been helpful to me and others. This is because, when the planted seeds failed to germinate, the nursed plants can be transplanted in those spaces of the dried-up crops. This over the years helps us get enough yields from our farm plots to support our household food needs amidst drought."*

For the farmers, nursing and transplanting provide an avenue to do sustainable farming within farm plots. The interview participants added that proper nursing and transplanting of crops can increase farm yields from five bags per acre to 10 bags as captured by A5:

> *"Nursing and transplanting can really improve crop yield. Last year, I did proper nursing and transplanting. There was no empty space on my farm plot. I paid attention to plant spaces too. And I must let*

TABLE 6 Contributions of CSA in reducing climate change vulnerability of millet and sorghum farmers.

Climate variable	Effects on millet and sorghum crops	Role of specific climate smart-agricultural practice for vulnerability reduction
Drought	Drying up of crops Drying up of seeds Hardening of soil for plant growth Poor yield Stunted growth of plants Wilting of crops	Terracing/contour farming to keep soil moisture Nursing and transplanting of seeds on farm plots to prevent total crop failure
Flood	Carrying away of crops Stunted growth of crops due to long stay in the water	Terracing and contour farming to allow water to run through the farm without affecting the crops Rotating of farm field when severe rains are anticipated to plant more flood resistant crop
Windstorm	Causing crops to fall resulting in pre-maturing Carrying away of the top nutrients of soil when is severe and persistent	Application of organic manure to farm fields for yield improvement Terracing and contour farming to support crops from falling when the windstorm incidence starts Integrating commercial trees with crops to check windstorm

> *you know that I got 15 bags of millet and sorghum together from a field I used to get less than eight."*

The farmers also indicated that terracing and contour farming help them improve soil nutrients for crop development. According to the farmers, due to drought, contour farming is done to retain the little drops of rains for crop growth and development. The adoption of contouring farming provides reservoirs to catch and retain rainwater permitting increased infiltration and more uniform distribution of the water as captured by C1:

> *"Contour farming as CSA practice has indeed helped us get more yield on our farm plots due to minimum water availability for crops to develop. Due to limited rainfall, the adoption of the practice has been useful. It helps us get more yield than when plants were planted on bare ground."*

3.6 Relationship between climate-smart agricultural practices of millet and sorghum and climate change vulnerability reduction

To establish the relationship between CSA and climate change adaptation, a chi-square analysis was performed. As represented by Table 7, except monocropping which has no association between CSA climate change vulnerability reductions among farm households in the Lawra Municipality, all the other CSA technologies essentially determine climate change risk reduction. For instance, land rotation/fallowing as CSA practice has a significant relationship with climate vulnerability reduction at 10% with chi-square value of 3.473. Agroforestry and manure application as CSA practices significantly relate with climate change vulnerability reduction at 5 and 1% with chi-square values of 3.014 and 4.571, respectively. Crop rotation and crop transplanting were also found to have association with climate change vulnerability reduction at 5 and 1% with chi-square values of 3.121 and 6.713, respectively. Finally, early weeding for weeds control and contour farming as CSA practices were significantly associated with climate change vulnerability reduction at 5% with chi-square values of 3.101 and 5.342, respectively. In conclusion, the chi-square revealed that as more farmers are recruited to be part of the study, the higher the possibility in adoption of any of these CSA practices.

3.7 Relationship between demographic characteristics of farmers and climate-mart agricultural practices adoption

The study presents the relationship between demographic characteristics of farmers and climate-mart agricultural practices adoption (see Table 8). As indicated in Table 8, age has a significant difference (at 10%) with crop rotation, agroforestry, manure application and crop transplanting but has no significant association with terracing. This implies that age influences the adoption decisions of crop rotation, manure application, crop transplanting and agroforestry. Farming purpose was found to be significantly related with crop rotation, terracing and crop transplanting at 5% with Chi Square values of 11.01, 8.91 and 7.13, respectively. The test found no significant difference between purpose of farming and manure application. Level of education of farmers has significant difference with crop transplanting at 1% with Chi Square value of 9.01 and agro-forestry at 5% with Chi Square value of 4.12. The test revealed no significant association between crop rotation and manure application. Farmers source of farming information is found to be significantly related with crop rotation at 1%, and agro forestry and terracing at 5%. Manure application and crop transplanting are associated with farmers source of farming information at 10%. Asset holding capacity has a significant difference with agro-forestry at 5% while terracing and manure application are associated with asset holding capacity at 10%. Gender and crop rotation has significant difference as well as terracing at 10%.

For climate information, the test results found an association between climate information and changing of planting dates, mixed cropping and improved crop varieties at 1 and 5%, respectively. The climate information was also found to be significantly related with inorganic fertilizer at 10%. This means that as farmers have access to climate information, the probability of farmer implementing changing of planting dates, mixed cropping and improved crop varieties. In

TABLE 7 Relationship between climate-mart agricultural practices of millet and sorghum and climate change vulnerability reduction.

CSA technologies	Adoption	Non- adoption	Total	χ^2-value
Land rotation/fallowing	331 (89)	27 (7)	358 (96)	3.473*
	11 (3)	4 (1)	15 (4)	
	342 (92)	31 (8)	373 (100)	
Transplanting	279 (75)	56 (14)	335 (89)	6.713***
	17 (5)	21 (6)	38 (11)	
	297 (80)	77 (20)	373 (100)	
Crop rotation	341 (91.4)	20 (5.4)	361 (96.8)	3.121**
	8 (2.1)	4 (1.1)	12 (3.2)	
	349 (93.5)	24 (6.5)	373 (100)	
Manure application	197 (52.8)	137 (37)	334 (89.8)	4.571***
	31 (8.3)	8 (2)	39 (10.2)	
	228 (61.1)	145 (38.9)	373 (100)	
Agro-forestry	99 (27)	251 (67)	350 (94)	3.014**
	11 (3)	12 (3)	23 (6)	
	110 (30)	263 (70)	373 (100)	
Erosion control by bunding	76 (20.4)	218 (58.4)	294 (96.7)	6.412**
	9 (2.2)	70 (19)	79 (3.3)	
	85 (22.6)	288 (77.4)	373 (100)	
Monocropping	117 (31)	211 (57)	328 (73.1)	0.052
	20 (5)	25 (7)	45 (26.9)	
	137 (36)	236 (64)	373 (100)	
Contour farming	125 (34)	213 (57)	338 (91)	5.342**
	9 (2)	26 (7)	35 (9)	
	134 (36)	239 (64)	373 (100)	
Early weeding	271 (73)	90 (23)	361 (96)	3.101**
	10 (3)	2 (1)	12 (4)	
	281 (76)	92 (24)	373 (100)	

***Denotes significant at 1% level, **denotes significant at 5% level and *denote significant at 10% level. Values in parenthesis are percentages.

terms of credit, inorganic fertilizer application and improved crop varieties were found to be significantly related at 1%. A significant difference was found between credit and agroforestry, improved animal husbandry and small-scale irrigation at 5%. Farm size was also found to be significantly associated with inorganic fertilizer, small-scale irrigation, mulching, terracing, and compositing at 5% whereas farm size was significantly associated with organic fertilizer at 1%.

4 Discussion

Climate-smart agriculture is widely acceptable as an approach to promote sustainable farming. Agricultural sustainability is critical to provide the food needs of the people especially those livelihoods that are strongly connected to the environment (Asrat and Simane, 2017; Anuga et al., 2019; Sullo et al., 2020). This interconnectedness between sustainable farming and agricultural sustainability places climate-smart agriculture as a core value to provide many households with their food demand. In this study, climate-smart agriculture is found to play key role in maintaining a balance between household food security and people's existence. The study observed that climate-smart agriculture has helped farmers to reduce their vulnerability to climate extremes. As revealed by the study, climate change dictates the food consumption pattern of many households through drought, floods, windstorms, imminent bush fires and dry spells. The results indicated that drought results in drying up of crops, stunted growth of crops and poor germination of crops while floods result in carrying away of crops, decay of crops and stunted growth due to long stay in the water. Windstorms as precipitated by climate change is found by the study to cause falling down of crops and carrying away of fertile top soil suitable for crop growth and development.

Despite these climate-induced events on crop growth and development, the study found that farmers are using climate-smart agricultural approaches to respond to them. The study found that crop rotation, land rotation/fallowing, crop transplanting, manure application, agroforestry, mono cropping, and contour/terracing are existing climate-smart agricultural practices which farmers are using to improve their crop yield amidst climate change. For instance, manure application, crop rotation and land rotation as CSA practices, according to the study, have aided farmers to maintain soil quality for

TABLE 8 Crosstabulation of demographic chrematistics and adoption of climate-smart practices.

Factors that influence CSA adoption	Climate-smart practices														
	Crop rotation			Agro-forestry			Terracing			Manure application			Crop transplanting		
	F	NF	χ^2	F	NF	χ^2	F	NF	χ^2	F	NF	χ^2	F	NF	χ^2
Age	47 (32)	99 (68)	8.14*	41 (28)	105 (72)	13.10*	69 (47)	77 (53)	9.72	53 (36)	93 (64)	4.5*	97 (66)	49 (34)	6.12*
Farming purpose	131 (90)	15 (10)	11.01**	114 (78)	32 (22)	4.71*	98 (67)	48 (33)	8.91**	127 (87)	19 (13)	5.7	76 (52)	70 (48)	7.13**
Educational qualification	99 (68)	47 (32)	3.17	112 (77)	34 (23)	4.12**	63 (43)	83 (57)	3.17	55 (38)	91 (62)	7.0	51 (35)	95 (65)	9.01***
Source of farming information	111 (76)	35 (24)	15.2***	103 (71)	43 (29)	11.0**	77 (53)	69 (47)	7.01**	91 (62)	55 (38)	3.1*	70 (48)	76 (52)	6.01*
Asset holding capacity	71 (47)	75 (53)	5.14	76 (52)	70 (48)	13.1**	57 (39)	89 (61)	7.90*	51 (35)	95 (65)	3.9*	48 (33)	98 (67)	2.1
Gender	31 (27)	115 (73)	3.97*	57 (39)	89 (61)	3.17	59 (40)	87 (60)	4.17*	49 (34)	97 (66)	2.7	71 (49)	75 (51)	4.17
Access to extension services	192 (93)	14 (7)	3.4***	197 (95)	9 (5)	7.1***	128 (62)	78 (38)	3.1**	159 (77)	47 (23)	4.1**	177 (86)	29 (14)	9.1***
Credit	57 (28)	149 (72)	5.17	201 (98)	5 (2)	4.6***	101 (49)	105 (51)	3.6**	67 (33)	139 (77)	3.01	77 (37)	129 (63)	4.15
Household size	61 (30)	145 (70)	3.51	198 (96)	8 (4)	5.9**	69 (33)	137 (67)	2.9**	127 (62)	79 (38)	3.9**	121 (59)	85 (41)	2.78
Access to climate information	201 (98)	5 (2)	4.5***	99 (48)	107 (52)	3.1*	77 (37)	129 (63)	3.91	79 (38)	127 (62)	2.06	88 (43)	118 (57)	3.47

***Denotes significant at 1% level, **denotes significant at 5% level and *denote significant at 10% level. Values in parenthesis are percentages.

the cultivation of their food crops. Crop transplanting is found to improve crop yield due to coverage of the farm plots with the transplanted seeds. Earlier studies have reported on the impact of climate change on food crop production, dry spells, meteorological droughts, flooding, and unreliable rainfall, cropping calendar changes and increased atmospheric temperature (Anwaruzzaman and Hoque, 2024; Kiprono et al., 2024). Changes in precipitation patterns increase the likelihood of short-run crops failure and long-run production declines. Populations in developing world, which are already vulnerable and food insecure, are observed to be most seriously affected. In South Asia, climate change is reported to have multiple effects on irrigated yield across the region with yield reduction reported to decline annually (Pequeno et al., 2024). In sub-Saharan Africa, yields of staple crops are reported to be on the decline with implications on household food security. Studies across Kenya, Tanzania, Uganda and many other countries in Africa reported decline in the yield of both staple and cash crops (Tongruksawattana and Wainaina, 2019; Twongyirwea et al., 2019). Nana (2019) study on climate change and agriculture in Burkina Faso reported that, climate change and its extremes such as drought floods and drought spells have placed constraints on activities of agriculture with dire repercussion on household food security. The study further reported that soil, water and land which are preconditions for successful farming have been affected by climate change and its extremes.

Given the implication of climate change on farm productivity, studies have found climate-smart farming practices as a sustainable solution to sustainable farming. As typified by the study, CSA has enabled farmers to meet their food needs in the Lawra Municipality. Earlier studies across the globe have provided evidence on the role of CSA on climate-change vulnerability reduction of farmers (Chitakira and Ngcobo, 2021; Nkumulwa and Pauline, 2021). For instance, a study by Nkumulwa and Pauline (2021) on the role of CSA in enhancing farmers' livelihoods and sustainable forest management in Kilidi District in Tanzania reported that CSA adoption by farmers has enhanced food security of many farm households. Chitakira and Ngcobo's (2021) study on the uptake of climate smart agriculture in peri-urban areas of South Africa's Economic Hub found that CSA practices such as mulching, cover cropping, crop rotation and the use of crop varieties have supported peri-urban farmers to meet their household needs. Using a combination of desktop studies, interviews and surveys to investigate the state of CSA in Nigeria, Cameroon and the Demographic Republic of Congo, Nwajiuba et al. (2015) found that smallholder farmers in these countries are already using climate smart approaches in their farming practices to improve their household food needs. Tesfaye W. et al. (2021) study in Ethiopia on climate-smart innovations and rural poverty reported that climate-smart technologies such as cereal-legume intercropping, minimum tillage and their combination (cereal-legume plus minimum tillage) has helped reduce the incidence and depth of poverty of smallholder farmers. CSA practices among farmers is central to promoting household needs not only in developing countries but in areas of developed destinations where agriculture still plays a significant role.

As found in the study, demographic characteristics such as household asset holding capacity, credit, extension services and climate information determine farmers' adoption decisions of the CSA practices. For instance, household asset holdings are indicators of wealth. Farmers who are wealthy are able to take advantage of climate smart agricultural technologies that are labor or capital intensive because of affordability. Studies have reported on household assets, and found that household assets exert a positive effect on adoption of climate smart agricultural technology for climate change vulnerability reduction (Van Aelst and Holvoet, 2018; Tongruksawattana and Wainaina, 2019). Other studies have reported mixed findings on household size, education, climate information as determinants in adoption of climate-smart agricultural technologies (Ali and Erenstein, 2017; Wu et al., 2018). Thus, households that have large membership tend to have enough labor force to assist in the adoption of agricultural technologies. For instance, adoption of agroforestry, manure application, manual irrigation and terracing require more supporting hands to implement them.

5 Conclusion and policy recommendation

Climate change scenarios indicate substantial reductions in the yield of staple food crops due to drought, high temperature, and rainfall variability. This observed negative impacts would directly determine food security of majority of household in sub-Saharan Africa. This call for dramatic change in food and agricultural food systems to include building farmers' resilience and adaptability to climate shocks. The study, using interviews and questionnaire with 146 smallholder farmers in the Lawra Municipality interrogated the contributions of CSA practices in reducing millet and sorghum farmers vulnerability to climate change. The study found a number of CSA practices such as weed control, land rotation, crop rotation etc. millet and sorghum farmers deployed to respond to drought, dry spells, and floods, which are annual climate events of the area. The study further found that adoption of CSA practices for climate change adaptation is influenced by access to credit and extension services, asset holding capacity and climate information. Given the importance of millet and sorghum to the people of the Municipality, in terms of food and other cultural functions and the criticality of weed control, land rotation and crop rotation, the study recommends the need for continuous technical support to include extension services, credit, and climate information to farmers to sustainably adopt these CSA practices for improved food production. Again, the study recommends the need for other non-governmental organizations and development partners especially Center for Indigenous Organization and Development and the German Development Cooperation Agency, which over the years have shown interest in promoting CSA practices among farmers, to support and promote the adoption of CSA by farmers. Promotion and adoption of CSA practices across the globe has the potency to improve agricultural returns, while facilitating access to sustainable food among farm households in Ghana and across the world.

5.1 Limitations of the study

The study was conducted in only Lawra Municipality, and generalizing the results to the whole region or country may not reflect specific situations. Further research in the area needs to be conducted across the region and country to provide more evidence-based findings that affect sustainable farming in the context of climate change and sustainable farming across the country.

Data availability statement

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

Ethics statement

There is no ethical approval from an appropriate ethics committee for this manuscript. SD Dombo University of Business and Integrated Development Studies is a new university, and institutional ethics review board is yet to be constituted. Given that there is absence of an institutional ethics review board of the University, informed consent was sought from the study participants, which the research team believed that, that was enough for a study on climate vulnerability reduction through climate-smart agriculture adoption.

Author contributions

GY: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. SB: Data curation, Writing – review & editing. ED: Supervision, Validation, Writing – review & editing.

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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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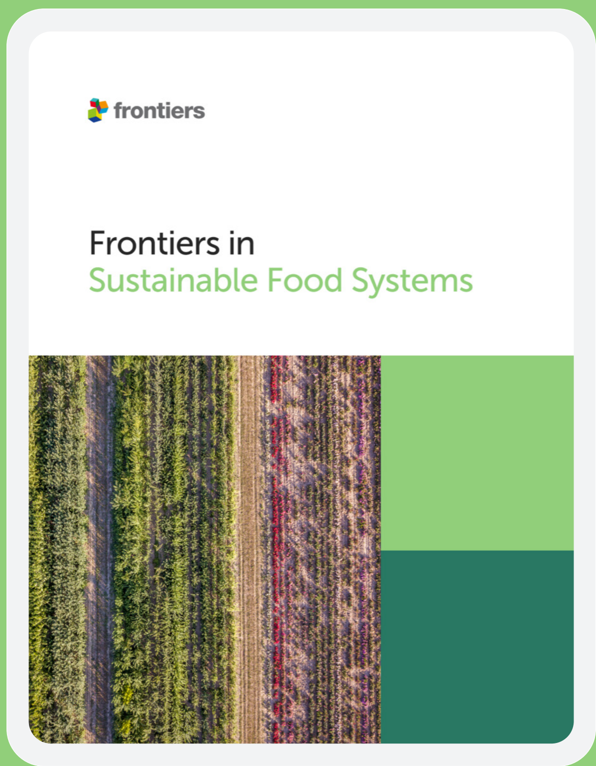

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