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Sustainable intensification of smallholder farming systems in Sub-Saharan Africa and South Asia

Edited by
Benjamin Karikari, Francis Tetteh, Fred Kizito, Folorunso Mathew Akinseye, Christopher Mutungi, Bekele Hundie Kotu and Terry Ansah

Coordinated by
Nurudeen Abdul Rahman

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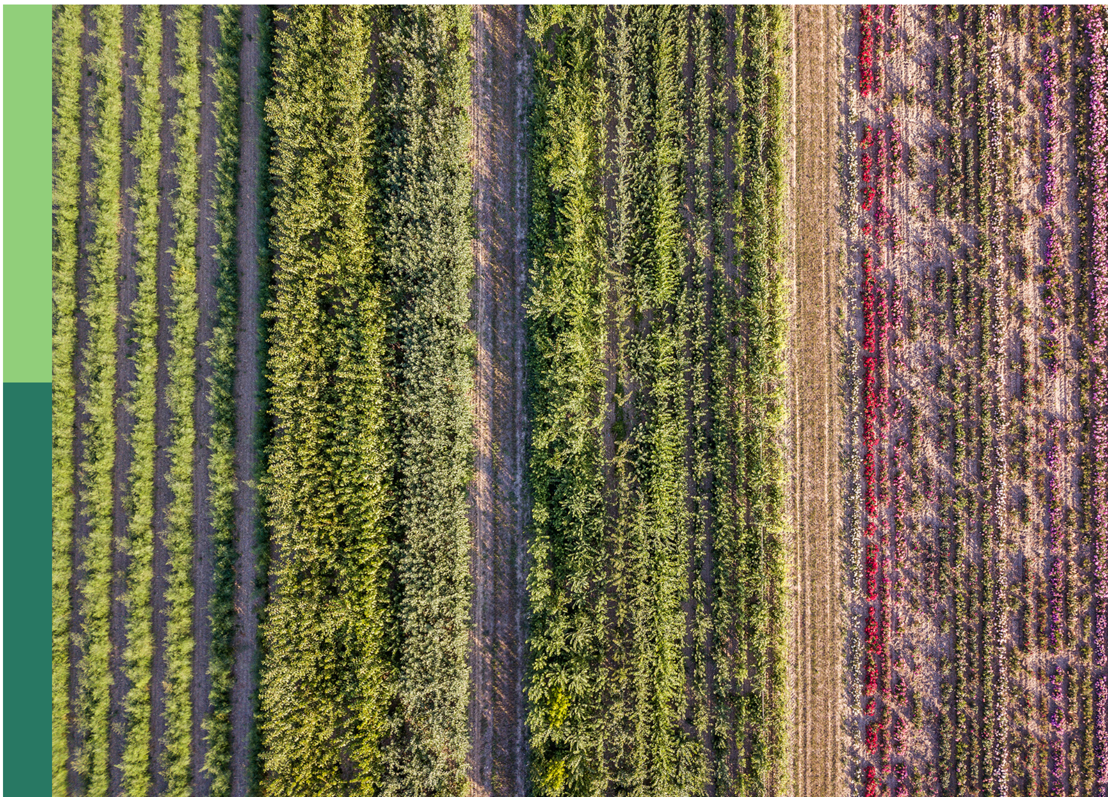

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Sustainable intensification of smallholder farming systems in Sub-Saharan Africa and South Asia

Topic editors
Benjamin Karikari — Laval University, Canada
Francis Tetteh — Soil Research Institute, Council for Scientific and Industrial Research (CSIR), Ghana
Fred Kizito — International Center for Tropical Agriculture, Kenya
Folorunso Mathew Akinseye — International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Kenya
Christopher Mutungi — International Institute of Tropical Agriculture, Tanzania
Bekele Hundie Kotu — International Institute of Tropical Agriculture, Ghana
Terry Ansah — University for Development Studies, Ghana

Topic coordinator
Nurudeen Abdul Rahman — International Institute of Tropical Agriculture, Ghana

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Ole Mertz,
University of Copenhagen, Denmark

*CORRESPONDENCE
Nurudeen Abdul Rahman
n.abdulrahman@cgiar.org

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Editorial: Sustainable intensification of smallholder farming systems in Sub-Saharan Africa and South Asia

Nurudeen Abdul Rahman[1]*, Bekele Hundie Kotu[2], Francis Marthey Tetteh[3], Benjamin Karikari[4], Folorunso Mathew Akinseye[5], Terry Ansah[6], Christopher Mutungi[7] and Fred Kizito[2]

[1]International Institute of Tropical Agriculture, Tamale, Ghana, [2]International Institute of Tropical Agriculture, Accra, Ghana, [3]Council for Scientific and Industrial Research-Soil Research Institute, Kumasi, Ghana, [4]Department of Crop Science, University for Development Studies, Tamale, Ghana, [5]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Thiès, Senegal, [6]Department of Animal Science, University for Development Studies, Tamale, Ghana, [7]International Institute of Tropical Agriculture, Dar es Salaam, Tanzania

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Editorial on the Research Topic
Sustainable intensification of smallholder farming systems in Sub-Saharan Africa and South Asia

Agricultural production in sub-Saharan Africa (SSA) and South Asia (SA) is mainly rainfall-dependent and dominated by smallholder farming systems. These smallholder farming systems with landholdings <5 ha produce about 80% of the food consumed in these regions (Chauvin et al., 2012; Jayne et al., 2014). Despite the contribution of the smallholder farmers to food production in these regions especially in SSA, productivity from their farms is low due to several factors such as low and declining soil fertility, limited use of external inputs, unfavorable policy, market and institutional arrangements, pests, and diseases, as well as the effects of climate change. The low productivity of agriculture among smallholder farmers exacerbates poverty levels since it is the main source of livelihood for more than 50% of the workforce in these regions (Odusola, 2021).

The world human population is projected to reach 9.7 billion persons by 2050, about half of the population will live in SSA and SA necessitating the production of more food to feed the growing population (Brandt et al., 2017; United Nations Department of Economic and Social Affairs Population Division, 2017). Increasing food production per capita in these regions through the conversion of marginal and grazing lands to productive arable lands is becoming limited and unsustainable due to the increasing demand for land for agricultural and non-agricultural uses (World Bank, 2007; Vanlauwe et al., 2017). Despite the success of agricultural intensification such as the Green Revolution type, it had some environmental limitations, and addressing these limitations evolved a sustainable intensification strategy (Pingali, 2012). Sustainable Intensification (SI) is the production of more food per unit area of land in an economically sound manner while reducing negative environmental, social, and human impacts (Pretty et al., 2011; Pingali, 2012; Smith et al., 2017). Promoting SI among smallholder farmers is critical for both regions to achieve the sustainable development goals (SDGs) set by the United Nations, particularly SDG1 (no poverty), SDG2 (zero hunger), SDG5 (gender equity), SDG 13 (climate action), and SDG 15 (life on land).

In this Research Topic, we present original research (14) and review (1) articles on recent scientific advances in SI of smallholder farms in SSA and SA. The articles examined SI of smallholder farms from different areas including productivity, natural resource management, mechanization, socio-cultural, and scaling up of SI innovations. The article by Akanmu et al. reviewed the role of agroecology techniques in the SI of smallholder farming systems. They reported that agroecology practices such as mixed cropping, agro-forestry, and crop-livestock systems among smallholder farms strategically ensure food security and sustainability. Another study by Goswami et al. discussed how the linkages in resource flow and its efficient use at the farm level affect the sustainability of farming systems. They reported that properties of resource interaction networks, the nature of resource interactions, and the type of farms affect the sustainability of farms.

According to Smith et al. (2017), the measure of sustainability in agricultural technology heavily relies on the productivity of the technology itself, particularly in terms of yield, which is considered the main outcome of sustainable intensification practices and the most commonly used indicator in SI literature. Three articles in this Research Topic studied productivity as the key area for SI of smallholder framing systems. Das et al. reported that low level of technical efficiencies is a limiting factor for agricultural production, highlighting the need to improve it for SI of smallholder farmers. Sasu et al. studied the use of alternative quality feed sources to increase the productivity and SI of smallholder livestock production. Bahta et al. reported the need to consider drivers such as infrastructure, access to information and inputs to help harness the potential of increasing productivity and SI of smallholder farms.

Low and declining soil fertility on smallholder farmers is the main cause of declining per capital food production in these regions particularly SSA (Sanchez et al., 1997). Three articles in this Research Topic examined soil fertility management as an entry point for SI of smallholder farming systems. Awoonor et al. studied soil suitability indexing using climate and soil physico-chemical properties for SI of smallholder farms. They reported that soils are heterogeneous and decisions on SI management of soils should involve prevailing local conditions. The study by Adjei et al. reported that continuous cropping on the same land over a long time leads to poor soil quality and unsustainable productivity. They recommended the use of integrated soil fertility management for soil quality improvement and sustainability of smallholder farmers under continuous cropping. Nakei et al. studied the importance of biological fertilizers to complement integrated organic and inorganic fertilizer use for SI of smallholder legume production.

Mechanization of agriculture helps to enhance productivity and reduce the unit cost of production (Pingali, 2007). Two articles in this Research Topic focused on mechanization as an entry point for SI of smallholder farms. The findings by Gershon et al. showed that a collective business model for mechanizing maize shelling enhanced mutual understanding, and respect for individual farmer differences, fostered better relationships, and reduced conflicts among smallholder farmers for SI of maize production. The article by Birhanu et al. also demonstrated the role of solar-based irrigation systems for efficient water management to improve productivity and the natural resources of smallholder farms. The solar-based irrigation systems provided a sustainable water supply for domestic water use, livestock, and vegetable production. The affordability of the panels by many smallholder farmers makes the system an emerging climate-smart technology for the SI of smallholder farms.

Understanding farmers' know-how in terms of agricultural production is a key in the SI of farming systems (Pretty et al., 2011). Two articles in this Research Topic assessed the role of farmers' thinking in the SI of their production. The study by Kalu et al. reported that farmers' age, sex, and years of experience in farming have a significant influence on farmers' choices in production and hence the need to consider farmers' desired attributes of production in SI of smallholder farms. Ngoya et al. reported that farmers' indigenous knowledge of addressing current agricultural production challenges has some gaps. Hence, a need for research and farmer learning for SI of smallholder farms.

Scaling and adoption SI innovations has been challenging in most cases and learning from past experiences helps to improve the success of scaling and adoption of agricultural innovations (Van Loon et al., 2020). Three articles in this Research Topic provide insights on scaling and adoption of SI innovations among smallholder farmers. Muthoni et al. reported the use of extrapolation suitability index for scaling SI innovation to increase adoption of innovation among smallholder farmers. The extrapolation suitability index uses geospatial framework to identify potential suitable sites for extrapolation of innovation based on factors (biophysical, socio-economic etc.) that limit productivity of the innovation. Another study tested a combination of participatory tools for scaling SI innovations (Mekonnen et al.). They reported that matching innovations to community needs, systems integration of innovations, stepwise approaches to enhance the adoption of innovations, building successful partnerships etc. as key factors to consider for facilitating wider scaling of SI innovations. Tufa et al. also examined why previous efforts and investments to scale conservation agriculture (CA) practices in southern Africa have not led to widespread adoption. They identified gaps in the order of awareness and adoption > training and adoption > demonstration and adoption rates of CA practices. They concluded that training and demonstrations are better conduits to enhance adoption than mere awareness creation.

Finally, the 15 contributions published in this Research Topic provide insights into the role and need for SI of smallholder farming systems in addressing the food demand needs of the growing populations in Africa and South Asia.

Author contributions

NAR: Writing – original draft, Writing – review & editing. BHK: Writing – review & editing. FMT: Writing – review & editing. BK: Writing – review & editing. FMA: Writing – review & editing. TA: Writing – review & editing. CM: Writing – review & editing. FK: Writing – review & editing.

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Conflict of interest

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EDITED BY
Benjamin Karikari,
University for Development Studies, Ghana

REVIEWED BY
Mustapha Mohammed,
University for Development Studies, Ghana
Rakesh S,
National Academy of Agricultural Research Management (ICAR), India
Jacob Ulzen,
University of Ghana, Ghana

*CORRESPONDENCE
Monica D. Nakei
✉ nakeim@nm-aist.ac.tz

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Preliminary symbiotic performance of indigenous soybean (*Glycine max*)-nodulating rhizobia from agricultural soils of Tanzania

Monica D. Nakei*, Pavithravani B. Venkataramana and Patrick A. Ndakidemi

Department of Sustainable Agriculture, Biodiversity and Ecosystem Management, School of Life Science and Bioengineering (LiSBE), Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania

Globally, the increase in human population continues to threaten the sustainability of agricultural systems. Despite the fast-growing population in Sub-Saharan Africa (SSA) and the efforts in improving the productivity of crops, the increase in the yield of crops per unit area is still not promising. The productivity of crops is primarily constrained by inadequate levels of soil nutrients to support optimum crop growth and development. However, smallholder farmers occasionally use fertilizers, and the amount applied is usually small and does not meet plant requirements. This is due to the unaffordability of the cost of fertilizers, which is enough to suffice the crop requirement. Therefore, there is a need for alternative affordable and effective fertilization methods for sustainable intensification and improvement of the smallholder farming system's productivity. This study was designed to evaluate the symbiotic performance of indigenous soybean nodulating rhizobia in selected agricultural soils of Tanzania. In total, 217 rhizobia isolates were obtained from three agroecological zones, i.e., eastern, northern, and southern highlands. The isolates collected were screened for N_2 fixing abilities under *in vitro* (nitrogen-free medium) and screen house conditions. The results showed varying capabilities of isolates in nitrogen-fixing both under *in vitro* and screen house conditions. Under *in vitro* experiment, 22% of soybean rhizobia isolates were identified to have a nitrogen-fixing capability on an N-free medium, with the highest N_2-fixing diameter of 1.87 cm. In the screen house pot experiment, results showed that soybean rhizobia isolate significantly ($P < 0.001$) influenced different plant growth and yield components, where the average shoot dry weight ranged from 2.49 to 10.98 g, shoot length from 41 to 125.27 cm whilst the number of leaves per plant ranged from 20 to 66. Furthermore, rhizobia isolates significantly ($P = 0.038$) increased root dry weight from 0.574 to 2.17 g. In the case of symbiotic parameters per plant, the number of nodules was in the range of 0.33–22, nodules dry weight (0.001–0.137 g), shoot nitrogen (2.37–4.97%), total nitrogen (53.59–6.72 g), and fixed nitrogen (46.878–0.15 g) per plant. In addition, the results indicated that 51.39% of the tested bacterial isolates in this study were ranked as highly effective in symbiosis, suggesting that they are promising as potential alternative biofertilizers for soybean production in agricultural soils of Tanzania to increase productivity per unit area while reducing production cost.

KEYWORDS

biological nitrogen fixation, rhizobial isolates, soybean, soybean-nodulating rhizobia, symbiotic performance

1. Introduction

The human population is rapidly growing with an estimate of around 9.7 billion people worldwide by 2050 (Vollset et al., 2020; Giller et al., 2021). Based on the study by Giller et al. (2021), the global governments' focus on human fertility and efforts to reduce mortality rates and food shortages have been the drivers for rapid population growth. While the world is realizing rapid population growth, the increase is higher in Sub-Saharan Africa (SSA), with an estimated 3.1 billion people in 2100 compared to 2.4 billion people in 2021 (Giller et al., 2021). The growth in the global human population exceeds the food required in terms of quantities produced, availability, and accessibility not only due to a decrease in fertile, available arable land for food production, which is utilized for the construction of modern infrastructures but also due to the vulnerability of food systems to climate change (Sorvali et al., 2021; Sadigov, 2022), with water and energy becoming the limiting factors (Nassary et al., 2020). At the same insight, global food production needs to be increased by 70% by 2050 to meet the food demand of 9.5 billion people (Kopittke et al., 2019; Wolde et al., 2021). To ensure food security in terms of quantity produced, accessibility, availability, and nutrients, the agricultural output needs to be optimized to meet the global rise in food demand (Aloo et al., 2021; Nakei et al., 2022).

Soybean (*Glycine max*) is among the common nutritious and high-value leguminous crops grown worldwide. The value of the crop is due to its high protein and oil content. Globally, soybean production covers about 6% of arable land and 50% of legume-growing areas. In different countries of Africa, mostly in Sub-Saharan Africa (SSA), including Tanzania soybean is grown (Wilson, 2013; Santos, 2019; Vanlauwe et al., 2019). In Tanzania, the crop has recently gained popularity and attention due to its nutritional value for human consumption and animal feeds, as well as higher global market demand (Chianu and Mairura, 2019). Soybean is among the leguminous crops which is important for food production and the improvement of agricultural systems. However, soybean productivity in SSA is not promising (Snapp et al., 2018). The low productivity is mainly due to soil fertility depletion caused by continuously growing and harvesting crops, which leads to inadequate levels of nutrients for optimum crop growth for optimum yield (Parveen et al., 2019). For instance, soybean production is estimated to be 1.1 tons/ha in SSA compared to 2.4 tons/ha at the global level.

Nitrogen is the first and most important plant-limiting element in agricultural soils and its deficit is usually remedied mainly by synthetic nitrogenous fertilizers (Simon et al., 2015). In SSA, smallholder farmers are the major producers of food crops, including legumes. Attaining higher crop yield under intensive and smallholder farming systems requires adequate levels of fertilizers to suffice the crop requirement for growth and development due to significant reduction in plant nutrients in agricultural soils as a result of continuous cropping and soil erosion (Elkoca et al., 2015). Smallholder farmers rarely use fertilizers due to the higher cost associated with synthetic fertilizers (Simon et al., 2015). The extensive and indiscriminate use of these artificial N-fertilizers has been linked to environmental pollution and consumer health concerns (Elkoca et al., 2015). Biological nitrogen fixation (BNF), a naturally occurring process, can supply an appreciable quantity of nitrogen to the soil. Biofertilizers made from the BNF process, especially involving native strains, have been reported to be the most effective, cheap, and environmentally friendly (Pirbalouti et al., 2006; Komarek et al., 2017). Leguminous crops largely depend on BNF symbiotic association with rhizobia for fixing nitrogen (Simon et al., 2015).

Soybeans (*Glycine max*), like other legumes, establish symbiotic relationships with rhizobia to form nodules in their roots, leading to the BNF process. Rhizobia play a fundamental role in N supply to ecosystems through their ability to fix N in symbiosis with legumes and promote the growth of plants as well as increase the productivity of crops (Peoples et al., 2009). This can be witnessed through several notable efforts to increase the productivity of soybean through the use of biofertilizers as an alternative source of nitrogen by some key joint research projects including N2AFRICA, administered by the International Institute of Tropical Agriculture (IITA) under the Consultative Group on International Agricultural Research (CGIAR) (Vanlauwe et al., 2019). Other notable efforts are made by different national research institutions, universities, national soybean improvement programs, and private sectors (Khojely et al., 2018). Through effective symbiosis, soybean annually can fix about 16.4 Tg of N from the atmosphere, about 77% of the total amount of N fixed by legumes (Hartman et al., 2011). Despite having the ability to associate symbiotically with rhizobia to fix nitrogen, soybean associates with a narrow diversity of symbiotically effective rhizobia to fix nitrogen and the efficiency of nitrogen fixation differs with the type of rhizobia species (Nakei et al., 2022). In the areas where the soybean is grown without inoculation with biofertilizers, the nodulation reports have been poor (Agoyi et al., 2017). The inoculation of soybean with symbiotically effective rhizobia results in effective nodulation and N_2-fixation; however, newly introduced rhizobia are observed to be outcompeted by well-adapted indigenous rhizobia, which are ineffective in N_2-fixation (Ampomah et al., 2008; Mathu et al., 2012; Kim et al., 2014). More effort is required for the isolation of effective indigenous rhizobia and commercialization to produce biofertilizers for easy accessibility and availability to smallholder farmers to enhance the sustainable productivity of soybean in Tanzania and SSA in general.

Despite the adaptation and competitiveness of indigenous rhizobia over commercial strains (Ampomah et al., 2008; Mathu et al., 2012; Kim et al., 2014), the competition is linked to environmental conditions, motility, production of different compounds, and phytohormones, yet, it is difficult to define the genetic basis of competitiveness (Vanlauwe et al., 2019). Although there are commercial strains, such as *B. diazoefficiens* USDA 110, which can fix nitrogen in a wide range of soils, their assurances still need careful on-farm trials in different soil types, including those with extreme acidic, salinity, and alkalinity. For this case, the use of indigenous rhizobia biofertilizer formulations is gaining the attention of different researchers to obtain indigenous strains of rhizobia that can effectively fix nitrogen in a wide range of soils, as well as the most effective ones in soils with extreme abiotic stresses. The availability of commercialized indigenous rhizobia species will provide easy accessibility to smallholder farmers for sustainable intensification of soybean productivity in their farming systems. The present study focused on isolating indigenous rhizobia from different soils of Tanzania that form symbiotic nodules with a specific soybean variety (Uyole IV) and testing their effectiveness under controlled conditions. The findings of this study enrich the knowledge that the researchers could tap into for the benefit of further studies on searching for the most effective indigenous rhizobia species and even the prospect of site-specific strains, especially those exposed to abiotic stresses.

2. Materials and methods

2.1. Description of the study area

The present study included isolates from nine regions (Iringa, Njombe, Ruvuma, Songwe, Rukwa, Mbeya, Morogoro, Arusha, and Kilimanjaro) of Tanzania and from mainly three agroecological zones. The isolates were collected from major soybean growing regions in the southern highlands zone (Iringa, Njombe, Ruvuma, Songwe, Rukwa, and Mbeya) of Tanzania. This zone is located between latitudes 7°C and 11.5°C S and longitudes 30°C and 38°C E with an elevation ranging from 302 to 2,925 m above sea level (m.a.s.l.). Rainfall is unimodal, falling from November to May with an annual rainfall of 1,650 mm and dry periods ranging from June to September (Mfwango et al., 2018). The mean annual temperature ranges from 7 to 32.2°C. The eastern zone included the Morogoro region, located between latitudes 5° and 9° S and longitudes 35° and 38° E. The mean annual temperature ranges from 15 to 32°C and the average annual rainfall is around 740 mm (Kacholi, 2020). The northern zone, Arusha, and the Kilimanjaro regions were included in the present study. Arusha region lies between latitudes 1 and 4°S and longitudes 34 and 37°E with an average annual rainfall of 873 mm. In contrast, the temperature ranges from 12.1 to 28.8°C. Kilimanjaro region lies between latitudes 2 and 4°S and longitudes 36 and 38°E. The average annual rainfall in the Kilimanjaro region ranges between 700 and 2,000 mm, and the temperature ranges from 12.5 to 27°C. The description of sampling sites in terms of altitudes is presented in Figure 1.

2.2. Nodules collection and isolation of rhizobia from root nodules

The study sites and the sampling location map were generated using QGIS 3.14.0 software (Figure 2). The collection of nodules was conducted during cropping seasons. In each region, three districts were selected, where three villages in each district were selected, and one field was selected for the collection of nodules in each village. Three plants with nodules at 50% flowering stage were randomly collected from each field, making a total of 243 plants, and treated as separate samples (Somasegaran and Hoben, 2012; Abrar and Letebo, 2017). The roots were cut at the crown level, kept in an icebox (around 4°C), and transported to the laboratory at Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania, for isolation, testing of effectiveness, and identification of effective rhizobia strains.

Before isolation of nodules, the media, Yeast Extract Mannitol Agar (YEMA), was prepared by adding 0.5 g of dipotassium phosphate (K_2HPO_4), 0.2 g of magnesium sulfate ($MgSO_4.7H_2O$), 0.1 g of sodium chloride (NaCl), 1 g of calcium carbonate ($CaCO_3$), 0.5 g of yeast extract powder, 10 g of mannitol, 15 g of agar bacteriological, and 0.025 g of Congo red in 1 L of distilled water. The pH of the media was adjusted to 7.0, which is optimum for the growth of rhizobia (Legesse, 2016), and the medium was sterilized by an autoclave at 15 pound-force per square inch (lbs) and 121°C for 15 min.

For isolation, nodules from each plant were detached from the roots and surface-sterilized in 70% ethanol for 30 s, followed by 1% sodium hypochlorite (NaClO) for 30 s and rinsed five times by using sterilized distilled water to remove the adhering sterilizing agents. From the sterilized nodules, one active nodule was selected by dissecting the nodules using a sterile surgical blade to observe the pinkish-red color as the indicator of leghemoglobin presence. Approximately 243 nodules were selected for the isolation of rhizobia. All the selected nodules were crushed separately with sterile toothpicks (Res, 2013) in sterile Eppendorf tubes containing 0.5 μL of 0.9% sodium chloride (NaCl) solution to obtain a milky suspension (Yuan et al., 2016). The suspension was streaked on a solidified YEMA medium; then, the plates were incubated at 28°C for 7 days (Abrar and Letebo, 2017). The plates were placed in an inverted position to avoid contamination by condensation of water. Bacterial growth on plates was observed every day after incubation for 7 days. Pure single colonies were then picked and then used for the N_2 fixation test, both under *in vitro* and screen house conditions.

2.3. *In vitro* screening for N_2 fixation test on solid N-free media

The intrinsic BNF ability of soybean nodulating rhizobia isolates was established on solid N-free media (NFM) in the *in vitro* assays before the screen house experiment. The NFM was prepared following the procedure described by Baldani et al. (2014). Then, the medium was sterilized using an autoclave at 1.05 kg/cm^2 pressure and a temperature of 121°C for 15 min. After sterilization, the medium was left to cool to about 50°C and then poured aseptically into sterile Petri dishes and left to solidify. After solidification, the pure rhizobial cultures were spot-inoculated on the medium. Each culture was considered as a treatment, the inoculation of each treatment was done in triplicates, and a non-inoculated plate was maintained as a control. The cultures were incubated at 28 ± 2°C for 7 days. After 7 days, the colony diameter and the yellow-colored zone around each colony were measured using a ruler and the values were recorded (Akintokun et al., 2019). The color changes in the media were observed to distinguish slow and fast growers.

2.4. Assessing the symbiotic effectiveness of isolates in the glass house

For the assessment of the symbiotic effectiveness of rhizobia in the screen house, the soil samples for the pot experiment were collected from the uncultivated area near the NM-AIST farm, and the fertility status was evaluated for its suitability to support rhizobia activities and growth of soybean plants. Three soil samples were taken from three spotted locations depending on the color of the soil because the area was too small. For each spotted location, about 1,000 g of soil samples were collected from 0 to 30 cm depth. Then, one composite soil sample was prepared by mixing three soil samples and removing the roots and crumbs. Prior to laboratory analysis, the soil was air-dried and sieved through a 2-mm mesh. The soil organic carbon was characterized by Walkley-Black's wet digestion

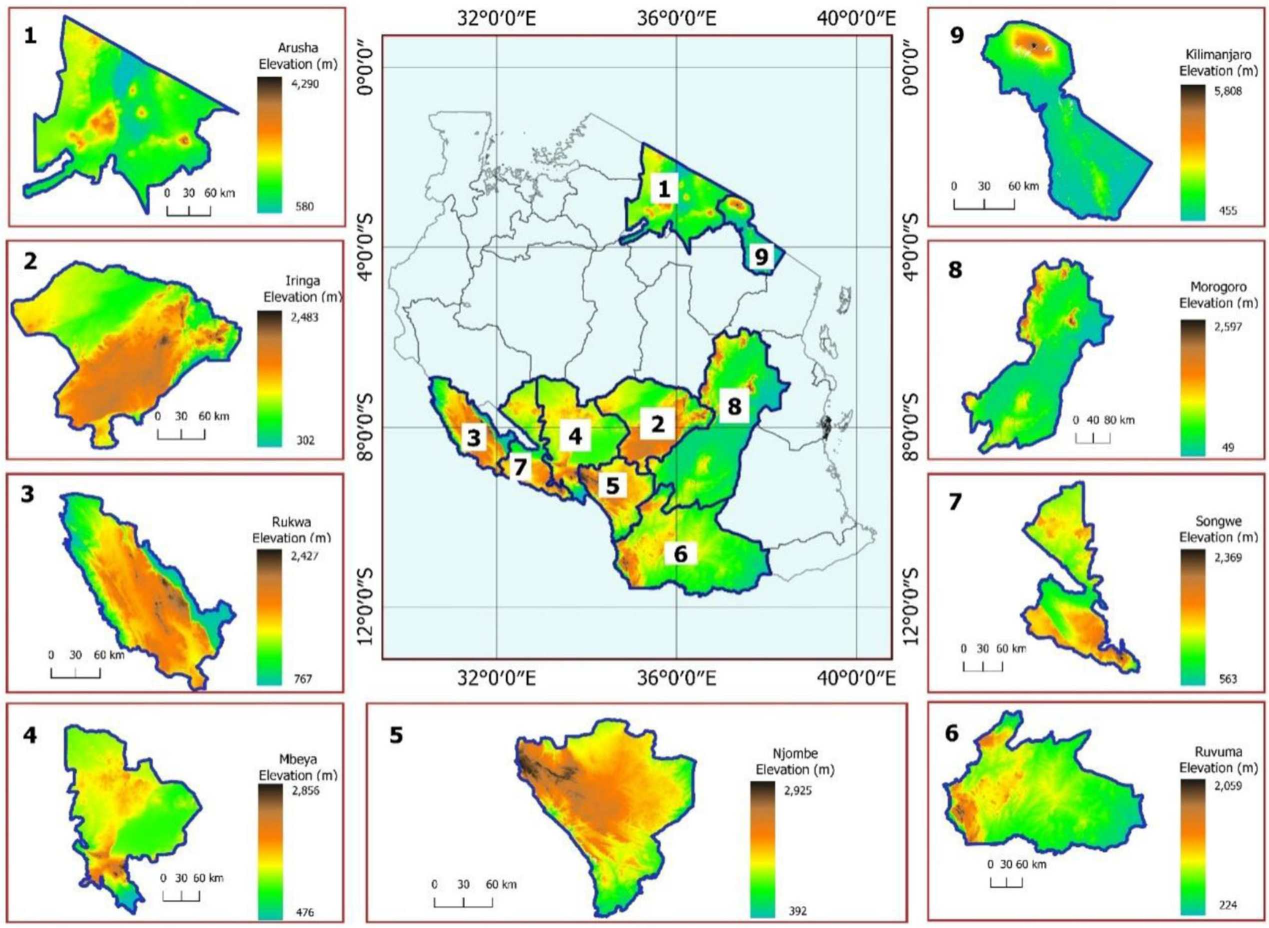

FIGURE 1
The map showing maximum and minimum elevations of the regions where soils and nodules were sampled.

(oxidation) method as described by Nelson and Sommers (1982). Soil pH was measured electrochemically in 1:2.5 (w/v) soil using the water suspensions potentiometric method previously described by Thomas (1982). Total nitrogen was determined by the micro-Kjedahl digestion–distillation method described by Motsara and Roy (2008). Extractable P was determined using the Bray 1 procedure because the soil sample had a pH of <7 (Bray and Kurtz, 1945). Cation exchange capacity was measured at pH 7 with 1 M ammonium acetate (NH_4OAc), and exchangeable cations K^+ and Na^+ were determined by flame photometer. In contrast, Ca^{2+} and Mg^{2+}, as well as micronutrients iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn), were determined by atomic absorption spectrophotometer (Thomas, 1982; Motsara and Roy, 2008). Moreover, the exchangeable sodium percentage (ESP) was calculated by dividing exchangeable Na by CEC (× 100) (Msanya, 2012). The ratings of physico-chemical parameters were based on the compilation of Motsara and Roy (2008).

For the pot screen house experiment, soybean seeds were sterilized with 70% ethanol for 1 min and soaked in 0.25% NaClO solution for 3 min. Then, the seeds were washed with distilled water five times before sowing to remove the disinfectants (Youseif et al., 2014). The seeds were aseptically transferred into a sterile Petri dish containing 1% water with tissue paper and allowed to germinate for 3 days at 25°C (Yuan et al., 2016). Then, the soil for growing crops was sterilized by oven drying. The germinated seeds (sprouts) were planted in 2-L plastic pots containing sterilized soil (oven dried at 70°C for 48 h (Sinegani and Hosseinpur, 2010). One germinated seed was planted per pot, and the pots were arranged in a complete randomized block design with three replicates. Each seedling was inoculated with 1 ml of 3-day-old rhizobia cultures, whereby the cells were calibrated to 10^9 ml^{-1} using a Macfarland scale at an optical density (OD) of 540 nm (Youseif et al., 2014). One positive control (commercial inoculum) and two negative controls (non-inoculated plants) and urea fertilizers at a recommended rate of 20 kg N/ha (Senkoro et al., 2017) were used as a comparison for the test cultures. All plants were given equal treatments by watering with nitrogen-free nutrient solution. The solution composition was $CaCl_2.2H_2O$ 294 g/l, $MgSO_4.7H_2O$ 123.3 g/l, KH_2PO_4 136.1 g/l, and K_2SO_4 87 g/l for macronutrients. Furthermore, Fe-citrate 6.7 g/l, $MnSO_4.H_2O$ 0.338 g/l, H_3BO_3 0.247 g/l, $ZnSO_4.7\ H_2O$ 0.288 g/l, $CuSO_4.5\ H_2O$ 0.1 g/l, $COSO_4.7H_2O$ 0.056 g/l, and $Na_2MoO_4.2H_2O$ 0.048 g/l were used for supplementation of trace nutrient elements (Maingi and Shisanya, 2006).

At 50% flowering (42 days after sowing), the plants were harvested to assess the presence of nodules in the roots. The isolates that managed to nodulate were proven as soybean-specific rhizobia.

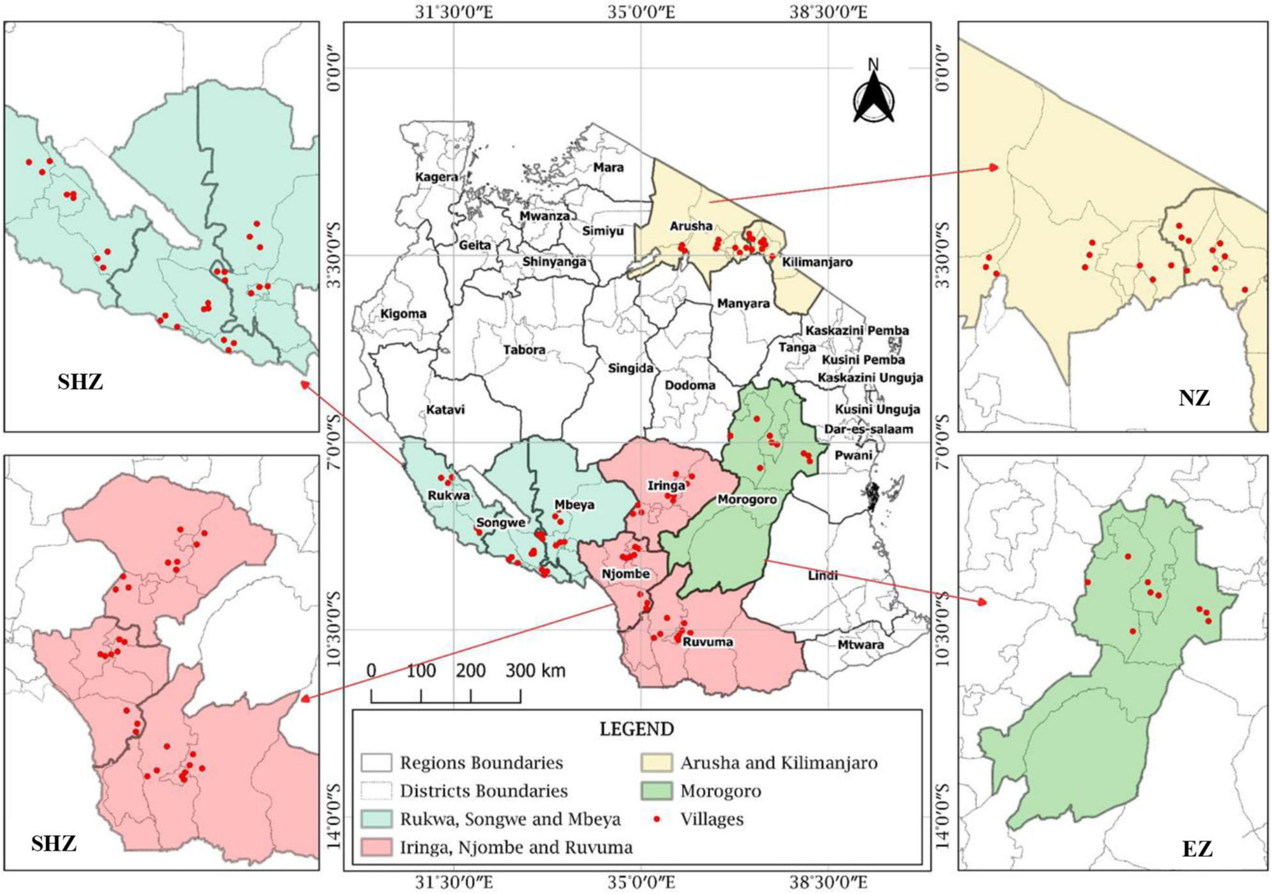

FIGURE 2
Map showing nodules sampling fields in different regions of Tanzania (SHZ-Southern Highland Zone, EZ-Eastern Zone, and NZ-Northern Zone).

To collect the data for above-ground biomass, the shoots were collected by cutting the plants at the ground level. The shoots were placed in paper bags and dried at 70°C for 48 h, as described by Legesse (2016), and their dry weights were recorded. The soil particle and the roots, which adhered to the detached nodules during the uprooting of plants, were separated by sieving through a 0.76-mm mesh and then washed gently with running tap water to clean the nodules and the roots completely. The roots were dried the same way as the shoots, all the nodules collected for each plant were counted, and their dry weight was determined in the same manner as the shoots and roots. The N concentration in the shoot was determined by using a micro-Kjedahl digestion–distillation method (Motsara and Roy, 2008). Total nitrogen (TN) and fixed nitrogen (FN) values per plant were calculated in above-ground biomass as shown in Equations 1 and 2 (Elkoca et al., 2015).

$$TN\ per\ plant\ (g) = Shoot\ dry\ weight\ (g) \times N\ (\%) \quad (1)$$

$$FN\ per\ plant\ (g) = TN\ in\ inoculated\ plants\ (g) - TN\ in\ non-inoculated\ plants\ (g) \quad (2)$$

The percentage increase/decrease in response/dependent variables was calculated from rhizobial treatments named Tanzania Soybean Rhizobia (TZSR) to compare the differences in inoculated, N-fertilized, and non-inoculated plants using Equation 3.

$$Percentage\ increase\ or\ decrease = \frac{Treatment - Control}{Treatment} \times 100 \quad (3)$$

The accumulation of shoot dry matter (DM) as the relative percentage of symbiotic effectiveness (S.E.) of isolates was calculated as shown in Equation 4. Nitrogen fixation was rated as highly effective $>$ 85%, effective 55–85%, lowly effective 35–54%, and ineffective $<$35% as described by Legesse (2016).

$$S.E.\ (\%) = \frac{Inoculated\ plant\ DM}{Nitrogen\ fertilized\ plant\ DM} \times 100 \quad (4)$$

2.5. Statistical data analysis

Different statistical methods were applied to analyze the collected data in terms of its distribution and correlation among the studied parameters. Data of all the collected nodules were statistically analyzed by R-software version 4.1.0, GenStat 15th Edition, and Jamovi version 2.3.2.0. The statistical difference for *in vitro* N_2 fixation test, among plant growth, yield components, and symbiotic traits, within and between the isolates was determined by one-way analysis of variance (ANOVA) following the factor effect model as shown in Equation 5. Tukey's-HSD multiple comparison test at a

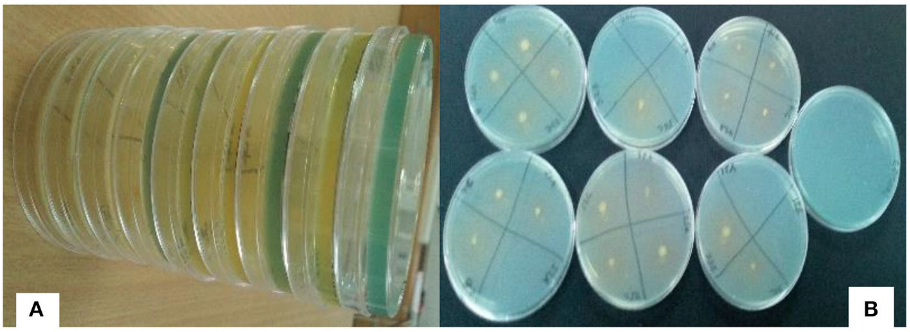

FIGURE 3
Yellow zones on solid nitrogen-free medium [**(A)** Color changes from blue to yellow, **(B)** Yellow zones around the rhizobia colony].

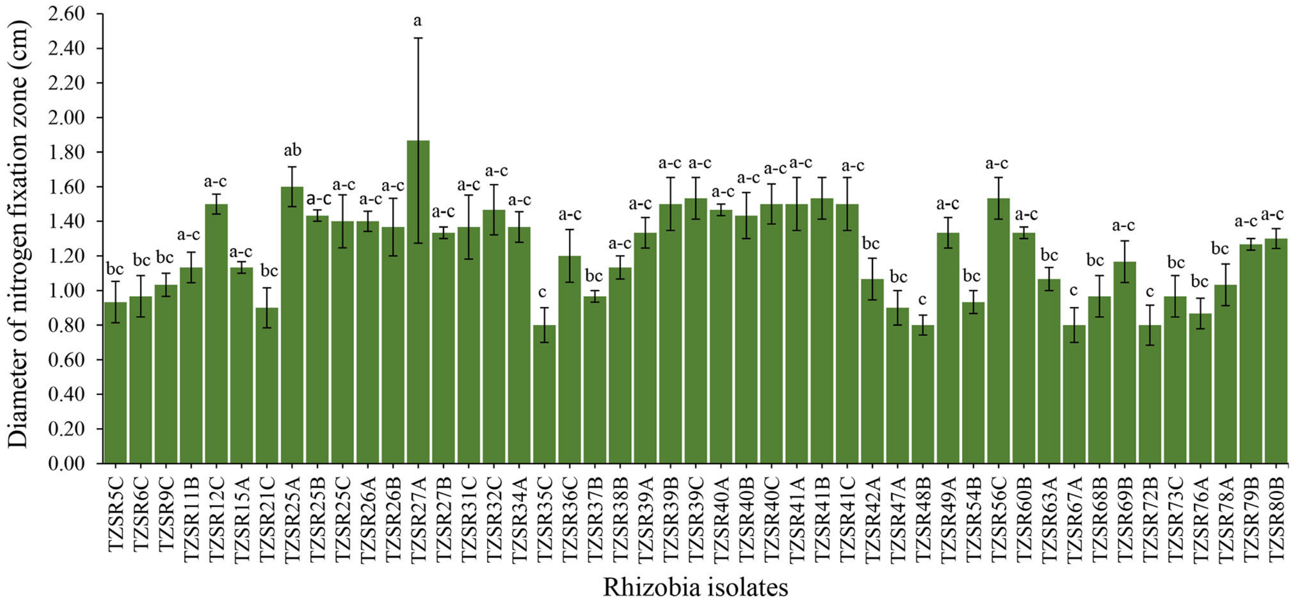

FIGURE 4
Nitrogen fixation zones of different rhizobia isolates on solid nitrogen-free medium (bars with different letters are statistically significantly different at $P < 0.05$).

threshold of 5% in GenStat 15th Edition was conducted to separate mean values among replications of the *in vitro* N_2 fixation test, plant growth, yield components, and symbiotic traits. Irrespective of the sample collection sites, some of the isolates did not show symbiosis with the rhizobia strains; hence physiographic effect was excluded from the analysis. Therefore, only one factor, the isolates (i.e., 47 isolates) that were capable of fixing nitrogen, was considered as the fixed main effect whereas replicates were treated as the random effect.

$$Y_i = u + \alpha_i + \varepsilon_i \quad (5)$$

where *Yi* is the observed response variable in the i^{th} factor; μ is the overall (grand) mean; α_i is the main effect of the factor isolates; ε_i is the random error associated with the observation of the response variable in the i^{th} factor.

To understand the relationship among studied parameters for the tested isolates, Pearson correlation matrix analyses for nodulation, growth, and yield components were performed using Jamovi software version 2.3.2.0. The trends in N_2 fixation traits were generated by using R-software version 4.1.0 Simpson (2015).

3. Results

3.1. *In vitro* nitrogen fixation abilities of soybean nodulating rhizobia isolates on solid nitrogen-free medium

About 217 rhizobia isolates were obtained from 243 nodules collected from different farmers' fields. The isolates were grown on NFM to test their abilities to fix nitrogen. Only 47 isolates (22%) were capable of growing on NFM as an indication of nitrogen fixation, and a change in the color of media from blue to yellow, indicating that the isolates are fast-growing rhizobia (Figure 3), was observed. The diameter of their nitrogen fixation zones on NFM varied significantly ($P = 0.001$) among 47 isolates (Figure 4), with an average of 1.23 cm.

TABLE 1 Physicochemical parameters of an experimental soil.

Parameter	Mean	Ratings	SD
Soil pH (H_2O)	6.60	N	0.01
Electrical conductivity (dS/m)	0.22	NYR	0.04
Organic carbon (%)	3.20	VH	0.07
Total nitrogen (%)	0.36	M	0.1
Extractable phosphorus (mg kg^{-1})	83.95	VH	0.63
Copper (mg kg^{-1})	2.28	H	0.05
Zinc (mg kg^{-1})	8.09	VH	0.01
Manganese (mg kg^{-1})	10.96	VH	0.36
Iron (mg kg^{-1})	10.53	VH	0.09
Exchangeable calcium [$cmol_{(+)}$ kg^{-1}]	14.05	VH	0.01
Exchangeable magnesium [$cmol_{(+)}$ kg^{-1}]	3.12	VH	0.09
Exchangeable sodium [$cmol_{(+)}$ kg^{-1}]	0.09	VL	0.01
Exchangeable potassium [$cmol_{(+)}$ kg^{-1}]	0.40	M	0.03
Cation exchange capacity [$cmol_{(+)}$ kg^{-1}]	19.12	M	0.56
Exchangeable sodium percentage (%)	0.56	M	0.05
Texture	Sandy clay loam		

VH, very high; H, high; M, medium; VL, very low; N, neutral; NYR, no yield reduction; S.D., standard deviation.

The largest N_2 fixation zone was observed in TZSR27A (1.87 cm), closely followed by TZSR25A (1.6 cm), and TZSR39C, TZSR41B, and TZSR56C, all of which had a fixation zone of 1.53 cm. At the same time, the smallest diameter (0.8 cm) was observed in TZSR35C, TZSR48B, TZSR67A, and TZSR72B.

3.2. The physicochemical properties of the soil used for the potting experiment

The physicochemical properties of the soil used for the pot experiment were evaluated and the results are presented in Table 1. The soil was sandy clay loam in texture, with soil reaction ranging from slightly acid (pH = 6.4 in $CaCl_2$) to neutral (pH = 6.6 in water). The percentage of organic carbon (OC) and total nitrogen were 3.2 and 0.36%, rated as very high and medium, respectively. The levels of extractable phosphorus (83.95 mg kg^{-1}) and micronutrients, such as zinc (8.09 mg kg^{-1}), manganese (10.96 mg kg^{-1}), and iron (10.53 mg kg^{-1}) were very high while that of copper (2.28 mg kg^{-1}) was high. Exchangeable bases, such as calcium [14.05 $cmol_{(+)}$ kg^{-1}] and magnesium [3.12 $cmol_{(+)}$ kg^{-1}] were very high, while potassium [0.4 $cmol_{(+)}$ kg^{-1}] was medium and sodium [0.089 $cmol_{(+)}$ kg^{-1}] was very low. In addition, the cation exchange capacity [CEC; 19.12 $cmol_{(+)}$ kg^{-1}] of the experimental soil was medium.

3.3. Nodulation and plant growth, shoot N, N-fixed, and symbiotic effectiveness

Rhizobia isolates were inoculated on soybean seedlings to assess their effects on plant growth parameters, as presented in Table 2, and the formation of symbiotic nodules and the modification of root system architecture in Figures 5A, B. There was a significant ($P < 0.001$) difference in the number of leaves, shoot length, nodules number, nodules dry weight, shoot dry weight, and total plant dry weight among the tested rhizobia isolates. Root dry weight differed significantly ($P = 0.038$) while there was a non-significant ($P = 0.081$) difference in root length among the rhizobia isolates. The highest nodule number per plant (22) was recorded in plants inoculated with isolated TZSR25B, whilst the lowest (0.33) was recorded in those inoculated with isolate TZSR34A. The highest nodule dry weight of 0.137 g was observed in plants inoculated with isolate TZSR41A whilst the lowest (0.001 g) was observed in those inoculated with isolate TZSR34A. The plants inoculated with TZSR41A also recorded the highest shoot dry weight of 10.98 g, corresponding to a 75.82% increase above the control (non-inoculated plants).

On the other hand, the lowest shoot dry weight of 2.49 g, corresponding to −4.73% over un-inoculated plants, was observed in plants inoculated with isolate TZSR21C. Interestingly, the highest root dry weight of 2.17 g corresponding to a 92.49% increase over un-inoculated plants was observed in plants inoculated with isolate TZSR69B, which had very few nodules, 1.33 per plant, but higher root density (Figure 5C). Conversant to this, the plants inoculated with isolate TZSR27B had the lowest average root dry weight, 0.574 g, which is 75.28% higher than un-inoculated plants but having many nodules, about 16.67 per plant.

The largest average total plant dry weight, 12.36 g corresponding to 73.95%, was observed in plants inoculated with isolate TZSR26B with the lowest 3.626 g corresponding to 11.22 % in rhizobia in those inoculated with isolate TZSR21C. The plants inoculated with rhizobia isolate TZSR41A yielded the highest average shoot length, 125.27 cm, corresponding to a 68.19 % increase over un-inoculated control plants. On the other hand, the lowest shoot length of 41 cm, corresponding to a 24.70% increase over un-inoculated plants, was observed in the plants inoculated with isolate TZSR34A. The largest number of leaves, 66 per plant, corresponding to 63.48%, was recorded in plants inoculated with isolate TZSR39B, while the lowest, 20, corresponding to a 52.38% increase, was observed in those inoculated with isolate TZSR39C. Interestingly, the highest root length of 43 cm corresponding to a 27.14% increase was recorded in plants inoculated with isolate TZSR40B whilst the lowest root length, 23.67 cm, corresponding to 22.4% lesser than un-inoculated plants, was recorded in plants inoculated with isolate TZSR63A.

Interestingly, the plants inoculated with two isolates, TZSR39C and TZSR41A, were observed to have consistently higher values for most of the studied plant growth and yield components except for root length and dry weight. On average, inoculated plants performed better than non-inoculated plants. Moreover, compared with positive control treatments, legume fix, and urea, rhizobia isolates performed better on average for all the tested parameters except for plant height and root dry weight, which was higher in plants where urea was applied. Surprisingly, three-quarters (19) of tested isolates (47) performed better than the legume fix except for shoot dry weight. However, half of the isolates performed better than urea except for root dry weight, in which 11 out of 47 isolates were better than urea.

Inoculation of soybean seedlings with rhizobia significantly ($P < 0.001$) increased shoot concentration of N, total N, fixed N, and symbiotic effectiveness of N (Table 3). The highest N concentration of 4.97% was recorded in plants inoculated with isolate TZSR27B;

TABLE 2 Growth and yield components of soybean as affected by inoculation with rhizobia isolates.

Isolate	Number of nodules	Nodule DW (g)	Shoot length (cm)	Number of leaves	Root length (cm)	Shoot DW (g)	Root DW (g)	Total plant DW (g)
TZSR5C	2.33^{bc}	0.007^{b}	47.67 (34.61)^{cd}	12.33 (20.81)^{b}	32.50 (9.61)^{ab}	3.22 (18.10)^{d}	0.63 (78.38)^{ab}	3.86 (16.59)^{d}
TZSR6C	1.33^{bc}	0.004^{b}	52.67 (32.74)$^{b-d}$	14.33 (2.73)^{b}	31.50 (8.38)^{ab}	3.05 (13.87)^{d}	0.79 (83.43)^{ab}	3.85 (16.30)^{d}
TZSR9C	1.00^{bc}	0.009^{b}	62.50 (47.08)$^{b-d}$	13.00 (12.72)^{b}	31.50 (8.84)^{ab}	2.99 (10.43)^{d}	0.94 (82.76)^{ab}	3.94 (18.36)^{d}
TZSR11B	2.33^{bc}	0.003^{b}	51.63 (39.44)$^{b-d}$	13.00 (27.41)^{b}	28.37 (−1.22)^{ab}	3.43 (23.93)^{d}	0.84 (82.76)^{ab}	4.27 (24.68)^{cd}
TZSR12C	9.33^{a-c}	0.048^{ab}	58.00 (46.43)$^{b-d}$	11.00 (14.63)^{b}	30.17 (−5.70)^{ab}	3.99 (33.91)$^{b-d}$	0.79 (83.15)^{ab}	4.82 (33.26)$^{b-d}$
TZSR15A	1.67^{bc}	0.017^{b}	43.00 (28.41)^{cd}	12.00 (11.22)^{b}	33.67 (12.63)^{ab}	2.84 (−93.15)^{d}	0.82 (82.20)^{ab}	3.68 (12.53)^{d}
TZSR21C	6.67^{a-c}	0.017^{b}	56.03 (44.79)$^{b-d}$	13.67 (30.87)^{b}	35.67 (9.00)^{ab}	2.49 (−4.73)^{d}	1.12 (88.04)^{ab}	3.63 (11.22)^{d}
TZSR25A	9.33^{a-c}	0.084^{ab}	75.97 (57.73)$^{a-d}$	19.67 (51.38)^{b}	30.17 (3.30)^{ab}	8.11 (62.07)$^{a-d}$	1.10 (87.10)^{ab}	9.52 (66.18)^{a}
TZSR25B	22.00^{a}	0.069^{ab}	72.53 (57.48)$^{a-d}$	14.00 (33.89)^{b}	26.83 (−9.33)^{ab}	4.90 (41.33)$^{a-d}$	1.66 (91.42)^{ab}	5.74 (43.89)$^{a-d}$
TZSR25C	13.33^{a-c}	0.095^{ab}	62.33 (50.43)$^{b-d}$	15.00 (38.28)^{b}	32.87 (6.40)^{ab}	4.67 (40.66)$^{a-d}$	0.99 (85.89)^{ab}	5.76 (44.08)$^{a-d}$
TZSR26A	10.33^{a-c}	0.045^{ab}	79.00 (60.14)$^{a-d}$	18.67 (48.42)^{b}	35.23 (17.22)^{ab}	7.79 (65.69)$^{a-d}$	1.32 (83.75)^{ab}	9.16 (64.84)$^{a-d}$
TZSR26B	11.33^{a-c}	0.046^{ab}	82.07 (62.28)$^{a-d}$	17.00 (45.74)^{b}	36.50 (21.29)^{ab}	10.78 (75.77)^{ab}	1.53 (90.82)^{ab}	12.36 (73.95)^{a}
TZSR27A	13.33^{a-c}	0.069^{ab}	75.80 (56.5)$^{a-d}$	15.33 (34.38)^{b}	30.00 (3.47)^{ab}	6.74 (56.63)$^{a-d}$	1.22 (88.34)^{ab}	7.70 (58.19)$^{a-d}$
TZSR27B	16.67^{a-c}	0.071^{ab}	124.17 (72.88)^{a}	19.67 (52.77)^{b}	34.67 (16.78)^{ab}	10.47 (74.15)$^{a-c}$	0.57 (75.28)^{ab}	11.11 (71.03)$^{a-c}$
TZSR31C	10.33^{a-c}	0.048^{ab}	79.00 (60.43)$^{a-d}$	14.33 (33.64)^{b}	39.00 (16.88)^{ab}	6.58 (42.11)$^{a-d}$	0.74 (80.14)^{ab}	7.37 (56.31)$^{a-d}$
TZSR32C	4.67^{a-c}	0.018^{b}	43.67 (27.78)^{cd}	7.33 (−33.07)^{b}	40.83 (23.32)^{ab}	3.01 (10.94)^{d}	0.71 (78.39)^{ab}	3.74 (13.84)^{d}
TZSR34A	0.33^{c}	0.001^{b}	41.00 (24.70) ^{cd}	9.33 (−3.33)^{b}	32.90 (12.76)^{ab}	3.15 (15.06) ^{d}	1.17 (86.37)^{ab}	4.32 (25.52)^{cd}
TZSR35C	1.33^{bc}	0.008^{b}	54.60 (41.76)$^{b-d}$	11.33 (14.78)^{b}	36.30 (19.85)^{ab}	2.84 (6.72)^{d}	1.01 (86.62)^{ab}	3.85 (16.46)^{d}
TZSR36C	0.67^{bc}	0.020^{b}	62.67 (48.35)$^{b-d}$	17.67 (44.28)^{b}	35.00 (17.05)^{ab}	3.26 (17.90)^{d}	0.93 (84.17)^{ab}	4.21 (23.58)^{cd}
TZSR37B	1.00^{bc}	0.029^{b}	42.73 (27.73)^{cd}	9.00 (−9.26)^{b}	31.67 (8.99)^{ab}	3.45 (24.25)^{d}	1.14 (86.07)^{ab}	4.62 (30.25)$^{b-d}$
TZSR38B	14.33^{a-c}	0.045^{ab}	90.33 (63.30)$^{a-c}$	15.00 (35.51)^{b}	28.00 (−6.02)^{ab}	3.87 (20.45)^{d}	0.77 (76.25)^{ab}	4.69 (31.29)$^{b-d}$
TZSR39A	12.33^{a-c}	0.050^{ab}	88.27 (62.57)$^{a-c}$	17.67 (44.07)^{b}	25.67 (−13.37)^{ab}	4.08 (30.17)$^{b-d}$	0.83 (78.45)^{ab}	4.96 (35.10)$^{b-d}$
TZSR39B	9.00^{a-c}	0.044^{ab}	81.33 (58.51)$^{a-d}$	66.00 (63.48)^{a}	41.90 (27.03)^{ab}	4.53 (38.41)$^{a-d}$	1.32 (89.26)^{ab}	5.89 (45.38)$^{a-d}$
TZSR39C	20.00^{ab}	0.096^{ab}	102.90 (69.60)^{ab}	20.00 (52.38)^{b}	32.33 (10.35)^{ab}	10.76 (74.54)^{ab}	0.70 (71.91)^{ab}	11.56 (72.14)^{ab}
TZSR40A	5.67^{a-c}	0.046^{ab}	71.43 (56.83)$^{a-d}$	16.33 (43.53)^{b}	30.67 (6.16)^{ab}	3.91 (21.22)^{d}	0.90 (42.05)^{ab}	4.85 (33.64)$^{b-d}$
TZSR40B	13.67^{a-c}	0.076^{ab}	73.43 (55.80)$^{a-d}$	14.33 (30.63)^{b}	43.00 (27.14)^{ab}	3.17 (8.95)^{d}	0.82 (82.30)^{ab}	4.73 (31.92)$^{b-d}$
TZSR40C	13.33^{a-c}	0.089^{ab}	93.10 (66.21)$^{a-c}$	19.00 (50.94)^{b}	31.00 (7.516)^{ab}	5.20 (36.12)$^{a-d}$	1.56 (74.88)^{ab}	6.85 (52.99)$^{a-d}$
TZSR41A	18.67^{a-c}	0.137^{a}	125.27 (68.19)^{a}	24.33 (53.41)^{b}	26.70 (−18.04)^{ab}	10.99 (75.82)^{a}	0.90 (84.26)^{ab}	11.69 (72.46)^{ab}
TZSR41B	12^{a-c}	0.0573^{ab}	90.37 (65.46)$^{a-c}$	17.33 (45.07)^{b}	29.97 (−1.48)^{ab}	5.38 (36.56)$^{a-d}$	0.52 (72.82)^{ab}	5.95 (45.92)$^{a-d}$
TZSR41C	12.00^{a-c}	0.056^{ab}	90.60 (65.88)$^{a-c}$	17.67 (48.28)^{b}	33.67 (11.73)^{ab}	4.93 (40.52)$^{a-d}$	1.03 (86.19)^{ab}	5.68 (43.34)$^{a-d}$
TZSR42A	8.67^{a-c}	0.090^{ab}	87.63 (63.99)$^{a-c}$	12.00 (21.80)^{b}	33.67 (12.86)^{ab}	3.97 (4.41)^{cd}	1.27 (88.83)^{ab}	4.77 (32.46)$^{b-d}$
TZSR47A	2.33^{bc}	0.015^{b}	50.00 (37.67)$^{b-d}$	13.33 (30.06)^{b}	35.33 (18.64)^{ab}	3.44 (24.09) ^{d}	1.76 (86.06)^{ab}	5.21 (38.26)$^{a-d}$
TZSR48B	1.00^{bc}	0.024^{b}	49.33 (36.90)$^{b-d}$	13.67 (26.41)^{b}	32.00 (10.02)^{ab}	3.49 (25.26)^{d}	0.93 (83.15)^{ab}	4.45 (27.65)^{cd}
TZSR49A	3.00^{a-c}	0.020^{b}	62.37 (48.36)$^{b-d}$	16.33 (32.22)^{b}	30.17 (5.01)^{ab}	4.50 (41.26)$^{a-d}$	1.16 (88.48)^{ab}	5.68 (43.29)$^{a-d}$
TZSR54B	1.33^{bc}	0.008^{b}	43.00 (28.10)^{cd}	13.67 (32.03)^{b}	53.33 (44.06)^{a}	3.08 (15.32)^{d}	0.83 (78.77)^{ab}	3.92 (17.93)^{d}
TZSR56C	2.33^{bc}	0.019^{b}	60.27 (48.29)$^{b-d}$	14.00 (25.00)^{b}	27.67 (−4.76)^{ab}	4.45 (26.82)$^{a-d}$	1.98 (92.11)^{a}	6.45 (50.06)$^{a-d}$
TZSR60B	11.00^{a-c}	0.068^{ab}	68.97 (55.02)$^{b-d}$	11.67 (20.45)^{b}	29.87 (2.45)^{ab}	6.76 (60.37)$^{a-d}$	1.14 (77.61)^{ab}	7.96 (59.57)$^{a-d}$
TZSR63A	1.67^{bc}	0.012^{b}	50.03 (37.82)$^{b-d}$	10.33 (7.23)^{b}	23.67 (−22.40)^{ab}	3.59 (27.30)^{d}	1.01 (85.93)^{ab}	4.61 (30.23)$^{b-d}$
TZSR67A	1.67^{bc}	0.008^{b}	39.87 (22.75)^{cd}	11.33 (15.69)^{b}	33.80 (15.20)^{ab}	2.76 (2.13)^{d}	1.11 (87.28)^{ab}	3.88 (17.12)^{d}
TZSR68B	1.33^{bc}	0.008^{b}	54.77 (43.13)$^{b-d}$	10.33 (7.22)^{b}	32.10 (9.08)^{ab}	3.86 (−32.86)^{d}	1.53 (88.82)^{ab}	4.40 (26.76)^{cd}
TZSR69B	1.33^{bc}	0.009^{b}	45.33 (31.27)^{cd}	13.00 (22.34)^{b}	33.33 (13.91)^{ab}	3.33 (−62.89)^{d}	2.17 (92.49)^{a}	4.51 (28.59)^{cd}

(Continued)

TABLE 2 (Continued)

Isolate	Number of nodules	Nodule DW (g)	Shoot length (cm)	Number of leaves	Root length (cm)	Shoot DW (g)	Root DW (g)	Total plant DW (g)
TZSR72B	3.67^{a-c}	0.015^{b}	58.37 (47.26)$^{b-d}$	12.00 (22.94)^{b}	42.00 (24.05)^{ab}	2.83 (−0.01)^{d}	0.63 (70.93)^{ab}	3.48 (7.45)^{d}
TZSR73C	0.67^{bc}	0.003^{b}	51.70 (39.68)$^{b-d}$	9.67 (4.38)^{b}	33.67 (14.66)^{ab}	3.06 (11.37)^{d}	0.70 (80.15)^{ab}	3.76 (14.46)^{d}
TZSR76A	0.67^{bc}	0.015^{b}	60.27 (48.71)$^{b-d}$	13.00 (28.91)^{b}	26.47 (−8.30)^{ab}	2.89 (−1.90)^{d}	1.22 (88.49)^{ab}	4.13 (22.10)^{cd}
TZSR78A	1.67^{bc}	0.003^{b}	58.10 (46.62)$^{b-d}$	11.00 (16.03)^{b}	33.03 (11.72)^{ab}	3.07 (5.86)^{d}	1.57 (90.84)^{ab}	4.64 (30.66)$^{b-d}$
TZSR79B	16.33^{a-c}	0.074^{ab}	70.50 (55.74)$^{a-d}$	17.00 (44.19)^{b}	39.00 (13.71)^{ab}	4.98 (46.48)$^{a-d}$	1.09 (86.95)^{ab}	5.81 (44.59)$^{a-d}$
TZSR80B	5.00^{a-c}	0.044^{ab}	84.33 (62.50)$^{a-d}$	16.33 (41.04)^{b}	37.67 (20.79)^{ab}	4.55 (39.02)$^{a-d}$	1.08 (84.36)^{ab}	5.67 (43.23)$^{a-d}$
Overall av.	7.11	0.039	67.42 (49.10)	15.40 (27.20)	33.30 (9.18)	4.66 (24.48)	1.08 (82.87)	5.69 (36.59)
PC-Lf	9.00^{a-c}	0.016^{b}	58.17 (46.34)$^{b-d}$	10.60 (13.47)^{b}	29.67 (2.30)^{ab}	3.80 (29.89)^{cd}	0.52 (52.23)^{ab}	4.33 (25.73)^{c}
PC-Urea	0.00^{c}	0.000^{b}	65.27 (52.27)$^{b-d}$	12.00 (21.11)^{b}	30.8 (4.64)^{ab}	4.41 (40.36)$^{a-d}$	1.26 (88.03)^{ab}	4.67 (31.03)$^{b-d}$
NC-0	0.00^{c}	0.000^{b}	31.00^{d}	9.33^{b}	28.67^{ab}	3.08^{d}	0.14^{b}	3.22 (0.00)^{d}
s.e.d.	4.75	23.23	13.31	6.04	6.33	1.66	0.45	1.72
P-value	<0.001	<0.001	<0.001	<0.001	0.081	<0.001	0.038	<0.001

Mean values with different letter(s), a–d in the same column differ significantly at P = 0.05. DW, dry weight; and the values presented in parenthesis/Bracket are the percentage increase per plant over un-inoculated plants in the values of measured parameters.

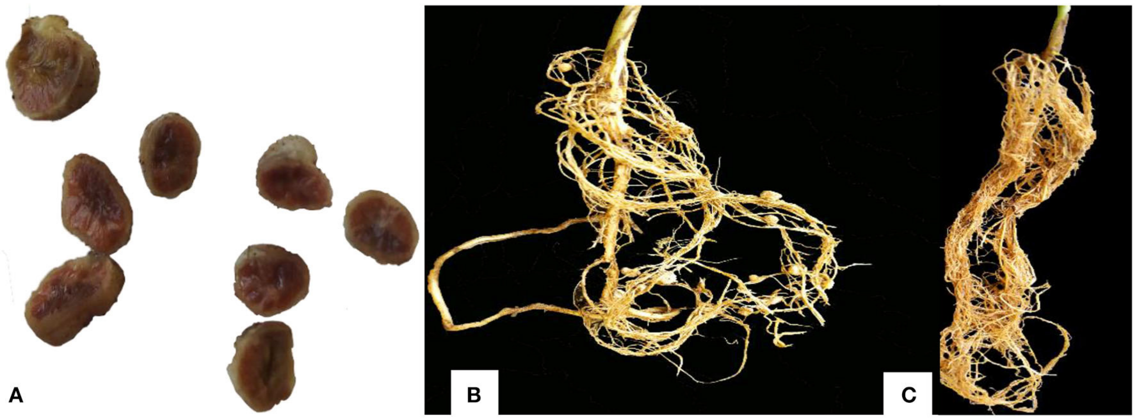

FIGURE 5
Effective soybean nodules and the root form of inoculated and un-inoculated plants [**(A)** Effective nodules, **(B)** root of inoculated plant having nodules, **(C)** root of un-inoculated plant, which did not form nodules].

the lowest, which was 2.37 %, was recorded in those inoculated with isolate TZSR37B. Conversely, inoculation of plants with rhizobia isolates TZSR41A yielded higher averages of total and fixed N levels of 53.59 and 46.878 g, respectively. The lowest level of total N (6.72 g) was recorded in the un-inoculated treatment (NC-0), whereas that of fixed N (0.15 g) was recorded in plants inoculated with isolate TZSR36C. Surprisingly, the plants inoculated with isolates TZSR25A, TZSR27B, and TZSR41A that have the highest fixed N are those with the highest shoot concentration of N and total N. Among the tested, 47 rhizobia isolates, 25 equivalents to 53% isolates were highly effective in symbiosis, 18 (38%) were effective, and 4 (9%) were lowly effective in symbiosis. In addition, among the isolates which are highly effective in symbiosis, TZSR25A (245.46 %) and TZSR26B (242.40 %) were ranked high in symbiotic effectiveness (Table 3).

3.4. Relationship for nodulation and plant growth and trends in N_2 fixation traits

The results indicated that nodulation (nodule numbers and dry weight) influenced different plant growth and yield components and interactions between various components (Table 4). There was a positive and significant ($P < 0.001$) correlation of total plant dry weight with shoot length, number of leaves, shoot dry weight, root dry weight, number of nodules, and nodules dry weight. Nodule dry weight was positively and significantly ($P < 0.001$) correlated with shoot length, shoot dry weight, and nodule numbers. Conversely, there was a positive and significant correlation ($P = 0.004$) of nodule dry weight with the number of leaves. There was a positive and significant ($P < 0.001$) correlation of nodule numbers with shoot length and shoot dry weight and number of

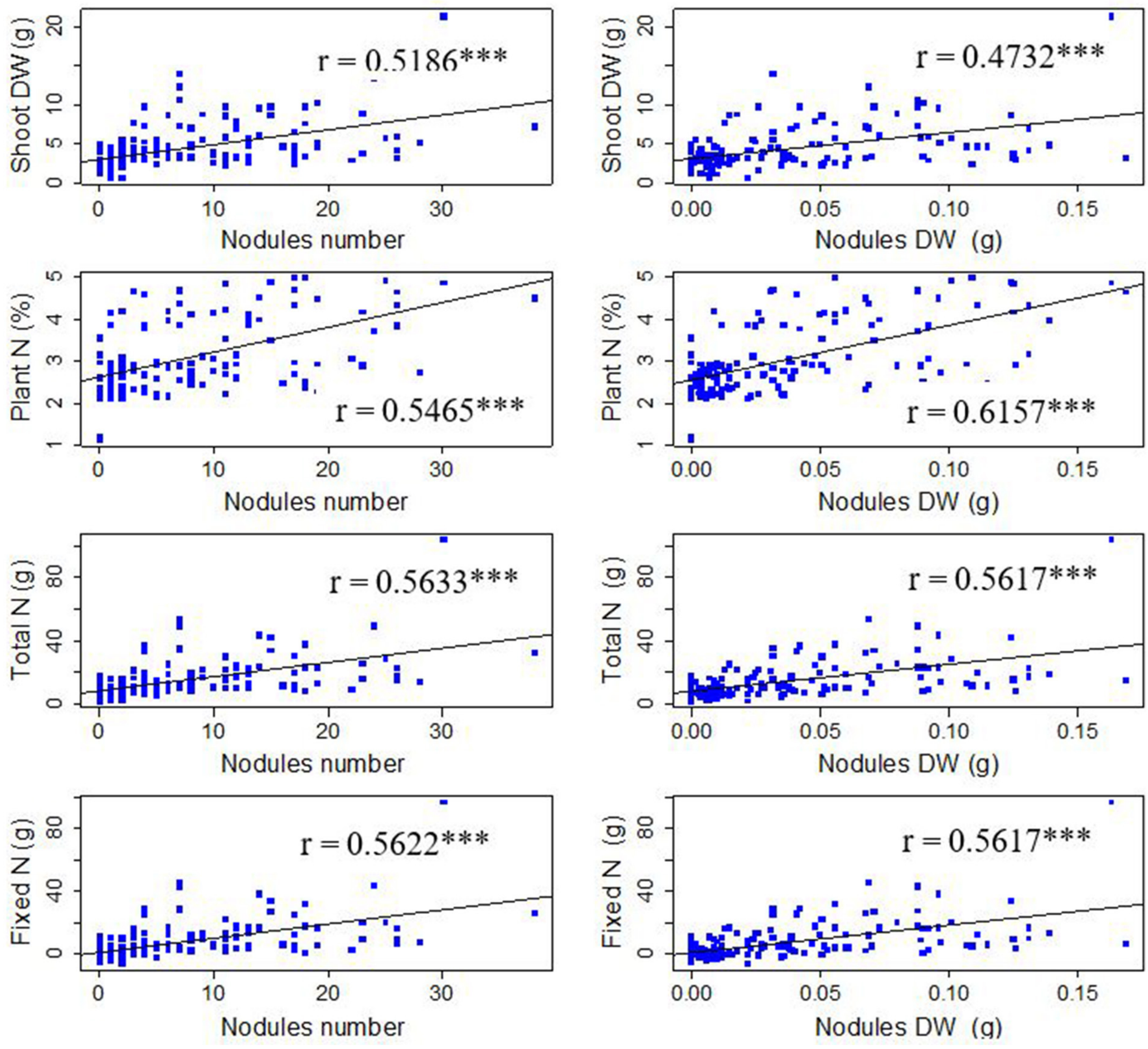

FIGURE 6
Trends analysis plots for SNF-related traits (*** significant at 0.001; n = 150, $P < 0.001$). N, Nitrogen; DW, Dry weight.

leaves ($P = 0.007$). A significant positive correlation ($P < 0.001$) was found in shoot dry weight with shoot length and the number of leaves. Moreover, root length was significantly ($P = 0.011$) correlated with the number of leaves. Furthermore, shoot length had a significantly ($P < 0.001$) positive relationship with the number of leaves.

A correlation analysis was performed across symbiotic traits identifying their relationships and strength in predicting SNF. All the symbiotic traits had positive significant ($P < 0.001$) correlations in predicting SNF at the flowering stage (Figure 6). The study found a significant positive correlation for nodule numbers with shoot dry weight ($r = 0.5186$), percentage plant N ($r = 0.5465$), fixed N ($r = 0.5622$), and total N ($r = 0.5633$). For the case of nodules dry weight, there was a significant relationship between nodules dry weight and shoot dry weight ($r = 0.4732$), percentage plant N ($r = 0.6157$), fixed N ($r = 0.5637$), and total N ($r = 0.5617$).

4. Discussion

4.1. *In vitro* N_2 fixation in nitrogen-free medium

The findings of this study demonstrate the wide variability in the tested indigenous rhizobial isolates' capacity to fix nitrogen on NFM. The varied capacities of rhizobia isolates in N_2 fixation are indicated by the difference in the diameter of the N_2 fixation zones (Aloo, 2021). The media color around the rhizobia colonies changes from blue to yellow due to the production of acidic metabolites during their growth on NFM (Baldani et al., 2014; Akintokun et al., 2019), which also indicates that the tested rhizobia are fast growers (Purwaningsih et al., 2021). Although there was no statistical significance between TZSR27A, TZSR25A, and the three isolates TZSR39C, TZSR41B, and TZSR56C, but the best isolate, TZSR27A, in terms of larger diameter of N_2 fixation

TABLE 3 Shoot N, fixed N, phosphorus, and symbiotic effectiveness of soybean with rhizobia isolates inoculation.

Isolate	Plant N (%)	Total N (g)	Fixed N (g)	S.E (%)	S.E rates
TZSR5C	2.460^{j-l}	7.98^{d}	1.262^{d}	74.00^{c}	Effective
TZSR6C	2.343^{j-l}	7.17^{d}	0.449^{d}	69.51^{c}	Effective
TZSR9C	2.733^{i-l}	8.28^{cd}	1.559^{d}	69.50^{c}	Effective
TZSR11B	2.457^{j-l}	8.432^{cd}	1.712^{d}	50.88^{c}	Lowly effective
TZSR12C	3.230^{d-k}	12.73^{cd}	6.012^{cd}	100.45^{a-c}	Highly effective
TZSR15A	2.730^{i-l}	7.98^{d}	1.259^{d}	66.86^{c}	Effective
TZSR21C	2.870^{g-l}	7.159^{d}	0.439^{d}	48.51^{c}	Lowly effective
TZSR25A	4.733^{ab}	52.021^{ab}	41.975^{ab}	245.46^{a}	Highly effective
TZSR25B	4.353^{a-c}	21.54^{b-d}	14.821^{b-d}	108.78^{a-c}	Highly effective
TZSR25C	3.950^{a-f}	18.48^{cd}	11.766^{cd}	105.40^{a-c}	Highly effective
TZSR26A	2.42^{3-l}	18.70^{cd}	11.983^{cd}	178.69^{a-c}	Highly effective
TZSR26B	2.457^{j-l}	26.62^{a-d}	19.905^{a-c}	242.40^{a}	Highly effective
TZSR27A	2.443^{j-l}	16.19^{cd}	9.473^{cd}	149.27^{a-c}	Highly effective
TZSR27B	4.970^{a}	37.70^{a-c}	30.981^{a-c}	241.49^{a}	Highly effective
TZSR31C	2.893^{g-l}	19.01^{cd}	12.298^{cd}	156.20^{a-c}	Highly effective
TZSR32C	2.617^{i-l}	7.78^{d}	1.061^{d}	69.38^{c}	Effective
TZSR34A	2.253^{kl}	7.095^{d}	0.375^{d}	71.39^{c}	Effective
TZSR35C	2.567^{i-l}	7.28^{d}	0.560^{d}	64.29^{c}	Effective
TZSR36C	2.203^{l}	6.86^{d}	0.145^{d}	73.61^{c}	Effective
TZSR37B	2.137^{l}	7.366^{d}	0.646^{d}	78.14^{c}	Effective
TZSR38B	2.600^{i-l}	9.03^{cd}	2.317^{d}	102.85^{a-c}	Highly effective
TZSR39A	3.860^{b-h}	15.72^{cd}	9.006^{cd}	101.43^{a-c}	Highly effective
TZSR39B	4.010^{a-e}	18.17^{cd}	11.458^{cd}	105.73^{a-c}	Highly effective
TZSR39C	4.600^{a-c}	37.320^{a-d}	22.246^{a-d}	183.927^{a-c}	Highly effective
TZSR40A	4.173^{a-d}	12.14^{cd}	5.422^{cd}	102.8^{a-c}	Highly effective
TZSR40B	4.233^{a-d}	13.49^{cd}	6.777^{cd}	103.90^{a-c}	Highly effective
TZSR40C	3.583^{c-i}	18.621^{c-d}	19.115^{a-d}	123.06^{a-c}	Highly effective
TZSR41A	4.877^{ab}	53.59^{a}	46.878^{a}	235.71^{ab}	Highly effective
TZSR41B	3.303^{d-j}	18.76^{cd}	12.047^{cd}	124.48^{a-c}	Highly effective
TZSR41C	4.677^{ab}	23.09^{b-d}	16.373^{b-d}	109.94^{a-c}	Highly effective
TZSR42A	2.953^{f-l}	10.73^{cd}	4.010^{cd}	106.60^{a-c}	Highly effective
TZSR47A	2.153^{l}	7.405^{d}	0.685^{d}	77.97^{c}	Effective
TZSR48B	2.217^{kl}	7.744^{d}	1.024^{d}	79.19^{c}	Effective
TZSR49A	3.870^{b-g}	17.40^{cd}	10.682^{cd}	101.81^{a-c}	Highly effective
TZSR54B	2.480^{j-l}	7.646^{d}	0.926^{d}	69.89^{c}	Effective
TZSR56C	2.770^{i-l}	12.33^{cd}	5.612^{cd}	105.13^{a-c}	Highly effective
TZSR60B	3.140^{e-l}	21.23^{b-d}	14.510^{b-d}	153.38^{a-c}	Highly effective
TZSR63A	2.290^{j-l}	8.223^{cd}	1.503^{d}	51.63^{c}	Lowly effective
TZSR67A	2.567^{i-l}	7.21^{d}	0.491^{d}	64.04^{c}	Effective
TZSR68B	2.160^{l}	8.333^{cd}	1.613^{d}	87.46^{c}	Effective
TZSR69B	2.473^{j-l}	8.237^{cd}	1.517^{d}	45.82^{c}	Lowly effective
TZSR72B	2.537^{j-l}	7.24^{d}	0.525^{d}	66.09^{c}	Effective

(Continued)

TABLE 3 (Continued)

Isolate	Plant N (%)	Total N (g)	Fixed N (g)	S.E (%)	S.E rates
TZSR73C	2.397^{j-l}	7.29^{d}	0.573^{d}	68.75^{c}	Effective
TZSR76A	2.527^{j-l}	7.24^{d}	0.524^{d}	68.18^{c}	Effective
TZSR78A	2.253^{kl}	6.87^{d}	0.155^{d}	68.18^{c}	Effective
TZSR79B	2.800^{i-l}	13.98^{cd}	7.259^{cd}	113.13^{a-c}	Highly effective
TZSR80B	2.840^{h-l}	12.96^{cd}	6.244^{cd}	105.91^{a-c}	Highly effective
NC-0	2.180^{l}	6.72^{d}	0.000^{d}	70.11^{c}	Effective
PC-Lf	2.930^{f-l}	11.13^{cd}	4.417^{cd}	87.71^{bc}	Highly effective
PC-Urea	3.293^{d-j}	14.60^{cd}	7.883^{cd}	100.00^{a-c}	Highly effective
s.e.d.	0.238	6.843	6.843	35.88	
P-value	<0.001	<0.001	<0.001	<0.001	

Mean values with different letter(s), a-l in the same column differ significantly at P = 0.05. S.E., Symbiotic effectiveness.

TABLE 4 Pearson correlation matrix for nodulation parameters (nodule number and dry weight), plant growth (root and shoot dry weight).

Growth parameters		Shoot length (cm)	Number of leaves	Root length (cm)	Shoot DW (g)	Root DW (g)	NDW (g)	Total Plant DM (g)
Shoot length (cm)	*r*	–						
	p-value	–						
Number of leaves	*r*	0.446***	–					
	p-value	< 0.001	–					
Root length (cm)	*r*	0.064	0.206*	–				
	p-value	0.428	0.011	–				
Shoot DW (g)	*r*	0.686***	0.263**	−0.044	–			
	p-value	< 0.001	0.001	0.588	–			
Root DW (g)	*r*	0.048	0.14	−0.064	0.091	–		
	p-value	0.557	0.083	0.431	0.261	–		
NDW (g)	*r*	0.632***	0.233**	0.136	0.473***	0.153	–	
	p-value	< 0.001	0.004	0.094	< 0.001	0.059	–	
Total Plant DM (g)	*r*	0.664***	0.284***	−0.054	0.979***	0.277***	0.461***	–
	p-value	< 0.001	< 0.001	0.509	< 0.001	< 0.001	< 0.001	–

Correlation coefficients (r) in individual cells represent each correlation between variables. Values with asterisk (*) are statistically significant different at *P < 0.05, **P < 0.01 and ***P < 0.001. DW, Dry weight.

zone ∼1.87 cm on NFM, would be considered highest, based on previous studies on different types of rhizobia species (Aloo et al., 2021).

4.2. Experimental soil's ability to support rhizobia and growth of soybeans

Soil health, especially soil fertility, is an important factor in the success of the biological nitrogen fixation process. Soil reaction and nutrient availability are among the components of soil fertility, which accounts for the effectiveness of the BNF process. Soil reaction (soil pH) determines the suitability of the given soil for certain rhizobia species. In contrast, different nutrients in the soil have different functions in ensuring the success of the BNF process (Nakei et al., 2022). Before authentication of the abilities of different rhizobial isolates under screen house conditions, different physicochemical characteristics of experimental soil were analyzed. The soil belonged to medium texture, Sandy clay loam (SCL), which is favorable for nodulation compared with heavy and light textured soils (Ali, 2016). The soil reaction of an experimental soil ranged from slightly acidic to neutral soil pH. This describes its suitability for most microbial populations and activities and is ideal for the availability of macronutrients and solubility of micronutrients that support plant growth and development (Zaharan, 1999; Giller, 2001; Zhang et al., 2018). The very high percentage of soil organic carbon and medium total nitrogen determined in this study suggests that the soil was well-enriched with organic matter contents (Giller, 2001). For rhizobial activities, a higher carbon level is important in providing energy, while a medium nitrogen level is sufficient for the biological nitrogen fixation process (Liu et al., 2018; Wang et al., 2020).

A very high level of available phosphorus determined in our experimental soil indicates its sufficiency for energy acquisition, storage, and utilization in the N_2 fixation process by the plant (Mmbaga et al., 2014; Abebe, 2017). Higher levels of micronutrients Zn, Mn, and Fe and a higher level of Cu signify the availability of these nutrients for plant uptake as well as serving various functions in the SNF process (González-Guerrero et al., 2014; Kasper et al., 2019). A higher level of zinc is crucial for plants and rhizobia during the SNF process for enhancing the expression of superoxide dismutase required during nodule development (Rubio et al., 2007). Manganese is involved in the initial stages of root colonization by rhizobia through the mediation of rhizobial lectin in binding to the root hair tips; its extreme levels enhance the formation of many symbiotic nodules and hence a more fixed amount of nitrogen (González-Guerrero et al., 2014). Extreme iron levels will facilitate the N_2 fixation process because iron is a component of the nitrogenase enzyme and a cofactor for other proteins (cytochromes and leghemoglobin) inside the nodule (Bonilla and Bolaños, 2009). The observed higher level of Cu is crucial for promoting N_2 fixation per nodule and raising the levels of N in plant tissues because copper is a member of the cytochromes that mediate energy transduction in bacteroids (Rubio et al., 2007; González-Guerrero et al., 2014).

Exchangeable bases, especially Ca, Mg, and K serve different important roles in soils for rhizobia activities as well as the growth and development of plants. The observed higher level of calcium is important in promoting the abundance of rhizobia and the development of roots, enhances the attachment of rhizobia to root hairs, root infection by rhizobia, and hence nodulation (Miwa et al., 2006; Bonilla and Bolaños, 2009; Capoen et al., 2009; Debona et al., 2017; Dabessa et al., 2018). Magnesium is a co-factor for urease and nitrogenase enzymes (Cakmak and Yazici, 2010; Gransee and Führs, 2013), and its involvement in the stabilization of cell membrane, nucleic acids, and ribosomes of the rhizobia (O'Hara, 2001) will increase the formation of the nodule (Kiss et al., 2004; Ramesh and Winkler, 2010; Peng et al., 2018). Moreover, the observed higher level of potassium will help in the regulation of water by the plant and influence the growth of roots, increasing the chances of infection by rhizobia and hence nodulation (Youssef et al., 2001; Wakeel et al., 2011; Mfilinge et al., 2014). In addition, the cation exchange capacity of an experimental soil was medium, suggesting a balance of the soil's exchangeable bases and acid, forming cations, Al^{3+} and H^{+} (de Borja Reis et al., 2021). Exchangeable sodium is very low; however, sodium is required in very small amounts in soil for SNF to avoid salinity stress. Its role in the soil can be replaced by the presence of potassium (Bonilla and Bolaños, 2009; Wakeel et al., 2011).

4.3. Nodulation and plant growth promotion by rhizobia isolates

The significant difference observed in the number of nodules and nodules' dry weight indicates the different abilities of rhizobia in forming symbiotic nodules (Gebrehana and Dagnaw, 2020). Nodulation, especially nodules' dry weight, is an important parameter in determining the competency of rhizobia in fixing nitrogen. Moreover, the composition of nodules, including bacteroids (N2 fixing rhizobia), proteins, enzymes, and nutrients, determines the dry weight of nodules as demonstrated by different isolates in this study. Different components perform different functions to ensure a successful and efficient N_2 fixation process (Schwember et al., 2019). However, nodule numbers may not exactly determine the extent of N_2 fixation when they miss some components such as leghemoglobin responsible for the supply of oxygen to bacteroids inside the nodules (Ott et al., 2005; Thilakarathna and Raizada, 2017). However, many nodules with higher nodule dry weight are an indication of effective symbiotic nodulation and host specificity (Alam et al., 2015; Gebrehana and Dagnaw, 2020). Similarly, in this study, the plants were inoculated with some isolates, and among them, TZSR41A had many nodules with the highest nodule dry weight. However, in this study, the shoot dry weight observed in plants inoculated with isolate TZSR21C was −4.73%, lesser than un-inoculated plants, which may be attributed to the modification of root system architecture by the inoculated rhizobia (Concha et al., 2020), which formed non-symbiotic nodules, hence, reducing the chances of nutrients uptake which affected the growth of shoot. Furthermore, the highest shoot dry weight and shoot length for a particular isolate suggest its effectiveness in N_2 fixation (Hungria and Vargas, 2000; Alam et al., 2015; Schwember et al., 2019).

In this study, the root dry weight differed significantly while there was a non-significant difference in root length among the rhizobia isolates. However, the lack of significant difference in root length may be attributed to the regulation of the growth of roots and modification in root system architecture by rhizobia during root infection and nodule formation (Concha et al., 2020). Furthermore, the reduced need of exploiting nutrients results in reduced root length, as the nutrients are made available around the rhizosphere either through fixed N or through solubilization of other nutrients. Root growth regulation and modification do not imply an absolute decrease in root length but rather balance a proportionality with the shoot for uptake and transportation of nutrients (Elkoca et al., 2015; Concha et al., 2020). Similarly, in this study, the highest root length of 43 cm recorded in TZSR40B is among the isolates with many nodules, indicating a balanced root system architecture and root growth as a result of reduced exploitation of nutrients induced by inoculation with rhizobia (Concha et al., 2020). However, extremely shorter roots, for instance, the one recorded in plants inoculated with TZSR63A, which is −22.4% lesser than un-inoculated plants, may be attributed to the alteration of root growth by promoting the lateral root formation likely through the modulation of auxin signaling by the inoculated rhizobia isolate (Zhao et al., 2018). Conversant to lesser root length, the root dry weight of the plants in the particular treatments have higher roots dry weight over un-inoculated plants. Overall, inoculated plants performed better than non-inoculated plants.

Moreover, compared with positive control treatments, legume fix, and urea, rhizobia isolates performed better for all the tested parameters except for plant height and root dry weight, which was higher in urea. Interestingly, in this study, the plants inoculated with two isolates, TZSR39C and TZSR41A, were observed to have consistently higher average values for most of the studied plant growth parameters except for root length and dry weight. Therefore, the above two isolates are potential in the production of rhizobia-based biofertilizers for intensification and sustainable production of soybean.

Inside the symbiotic nodules is where the rhizobia associate with plants to fix nitrogen and hence promote the growth and development of plants. It is highly likely that many symbiotic nodules with higher dry weight per plant lead to an increased level of fixed nitrogen and nutrient uptake by plants. This is supported by the observations made in this study on the significant positive correlations of nodule numbers and nodule dry weight with other plant growth parameters. Similar to this study, other researchers have reported significant correlations among the mentioned parameters (Appunu and Dhar, 2006; Youseif et al., 2014; Elkoca et al., 2015; Wang et al., 2020). This study showed a strong and significant positive correlation between the number of nodules and nodule dry weight. However, the correlation between nodules number and dry weight may be due to collinearity but many nodules may not necessarily exhibit higher dry weight due to the size and the composition of the nodules (Ott et al., 2005; Thilakarathna and Raizada, 2017). In addition, the observed positive significant correlation between nodulation (nodule numbers and dry) and shoot length, shoot dry weight, and the number of leaves suggests that the increase in nutrient availability is a result of increased symbiotic nodulation upon inoculation and hence above-ground biomass (Elkoca et al., 2015; Gitonga et al., 2021; Ozede and Olubukola, 2021). Although in this study, nodulation (nodules number and dry weight) has been used as a major parameter in measuring SNF, the nodules number is observed to have several limited proxy values in determining effective symbiosis (Hungria et al., 2001; Thilakarathna and Raizada, 2017); hence nodules dry weight is used as a better proxy (Thilakarathna et al., 2021). The observed significant positive correlation among different individual plant growth parameters can be linked to the increased growth and development of healthy plants through the availability of nutrients (Alam et al., 2015; Ntambo et al., 2017) mediated by N_2 fixation attributed to inoculation of soybean seedlings with rhizobia (Aloo et al., 2021).

4.4. Symbiotic parameters as influenced by isolates

The significant increase in shoot nitrogen concentration, total N, fixed N, and symbiotic effectiveness observed among the tested isolates clearly demonstrates that the isolates were capable of fixing nitrogen under screen house conditions but in varying abilities. The increase in shoot N concentration corroborates (Iturralde et al., 2019), who found that inoculation increased nitrogen concentration in shoots of soybean plants. On the other hand, Subramanian and Kim (2014) reported an increase in soybean shoot total nitrogen with inoculation by symbiotically effective rhizobia. From this study, the plants inoculated with three isolates, TZSR25A, TZSR27B, and TZSR41A, that have the highest fixed N are those with also the highest shoot concentration of N and total N. In addition, inoculation of plants with two isolates, TZSR25A and TZSR26B, yielded high symbiotic effectiveness, suggesting that fixed N contributed to the total N content of the plant shoot. These findings agree with those of Dashti et al. (1998) that inoculation of soybean with effective rhizobia significantly increased fixed N, which ultimately contributes to the increment of total nitrogen in the shoot of plants. Chibeba et al. (2017) indicated that different rhizobia isolates had different abilities in fixing nitrogen and hence different relative symbiotic effectiveness. The 94% of isolates, which were effective in N_2 fixation, implies that most of the isolates tested in this study had a higher capacity to fix nitrogen under controlled conditions. Furthermore, on-farm testing under field conditions is recommended for isolates, which performed well than urea treatment in the screen house potted experiment. This finding also suggests that these effective isolates can potentially be used to improve soybean productivity and N budget, hence contributing to sustainable intensification of the agricultural system, specifically in soybean production.

Nodulation (nodules number and dry weight) is the first symbiotic trait to be observed before measuring other traits, namely shoot dry weight, percentage plant N, and total N. This is because the measurement of other traits is dependent on the extent of nodulation and their influence on the variation of other SNF traits. The significant positive correlation between nodulation (nodules number and nodules dry weight) and shoot dry weight (Unkovich et al., 2010) suggests that inoculation of soybean seedlings with rhizobia increased N_2 fixation. These results are in agreement with Alam et al. (2015) and Ntambo et al. (2017) who reported an increase in shoot dry weight as a measurable indicator of increased nitrogen concentration in plants resulting from symbiotic N_2 fixation through inoculation. The nitrogen concentration in plant shoot biomass is the determinant of total and fixed nitrogen in plants inoculated with effective rhizobia (Elkoca et al., 2007; Ogutcu et al., 2008). The study conducted by Elkoca et al. (2015) and Chibeba et al. (2017) demonstrated that inoculation of legumes with effective rhizobia increased the concentration of N, fixed N, and total N concentration in plants. Moreover, different rhizobia isolates differ in symbiotic effectiveness, although the difference among some isolates was not statistically significant due to higher variation, but they are numerically different, and this is relative to their abilities to fix nitrogen (Chibeba et al., 2017). According to rating guidelines by Legesse (2016), the isolates with symbiotic effectiveness value of >85% are considered highly effective in nitrogen fixation regardless of their variation as observed in this study.

5. Conclusion and recommendations

The availability of nutrients to suffice crop requirements is crucial in increasing the productivity of crops. Nitrogen, the first and most limiting nutrient for crops is required in larger quantities for growth, development, and optimum yield. The available nutrient sources, synthetic, organic, and commercial biofertilizers, have been there, but still, there is an appreciable deficiency of nutrients including nitrogen in smallholder farming systems. It is high time to explore the effective indigenous species of rhizobia and commercialize their biofertilizer formulations for easy availability and accessibility to smallholder farming systems. The tested indigenous rhizobia species in this study demonstrated varying abilities with some highly effective ones in nodulation and promotion of plant growth and yield components as indicated by nodules and shoot dry weight of up to 0.137 and 10.99 g per plant and the increase in shoot dry weight of 75.82% for the plants inoculated by isolate TZSR41A. Moreover, about 50% of the isolates showed higher nitrogen-fixing abilities as indicated by their symbiotic effectiveness. Enhancement of plant growth and yield components results from increased nutrient availability and uptake. However, on-farm testing under field conditions is recommended for isolates, which performed well in the screen house potted experiments. Nevertheless, the availability of nutrients should be sustainable to ensure sustainable crop production. The two aspects, nutrient availability and crop productivity, should consider factors such as affordability by farmers, environmental safety, and effectiveness to ensure safe and nutritious food security. Therefore, the studied isolates are the potential for formulating biofertilizers for field applications and sustainable soybean productivity in Tanzania upon confirmation under field conditions.

Data availability statement

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

Author contributions

MDN, PAN, and PBV: conceptualization and methodology. MDN: original draft preparation. PAN and PBV: review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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

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EDITED BY
Folorunso Mathew Akinseye,
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Kenya

REVIEWED BY
Rakesh S.,
National Academy of Agricultural Research Management (ICAR), India
Vesna Radovanović,
University of Belgrade, Serbia

*CORRESPONDENCE
Benedicta Essel Ayamba
✉ esselbenedicta@yahoo.com

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Soil quality and fertility dynamics under a continuous cassava-maize rotation in the semi-deciduous forest agro-ecological zone of Ghana

Eric Owusu Adjei[1], Benedicta Essel Ayamba[2]*, Mohammed Moro Buri[2,3], Nathaniel Biney[2] and Kwasi Appiah[1]

[1]Department of Soil Resource Management, CSIR College of Science and Technology, Academy Post Office, Kwadaso, Kumasi, Ghana, [2]Soil Fertility and Plant Nutrition Division, CSIR-Soil Research Institute, Academy Post Office, Kwadaso, Kumasi, Ghana, [3]Faculty of Natural Sciences and Environmental Management, CSIR College of Science and Technology (CCST), Kumasi, Ghana

The practice of crop rotation is known to significantly influence soil nutrient dynamics, depending on the type of rotation and the crops involved. As such, a field study was conducted to find out the effect of continuous cassava-maize rotation, where mineral fertilizer was only applied to the maize crop, on soil nutrients dynamics and soil quality thereof under varying rotation periods. The study revealed that Soil Organic Matter (SOM) and levels of soil nutrients, such as total nitrogen, available phosphorus and exchangeable cations (potassium, calcium, magnesium, and sodium) significantly declined with rotation period. Long term maize–cassava rotation led to subsoil (20–50cm) acidification. Soil quality as measured by Carbon Management Index (CMI) on the different aged rotations decreased with age, with the longest rotation period giving the least quality. These results and observations imply that long term cassava-maize rotation reduced soil quality and the resilience of the cropping system for continuous sustainable crops production. A regression analysis of soil nutrients with CMI under the continuous cassava-maize rotation identified the crucial role of soil total N ($r^2 = 0.56$) and exchangeable K ($r^2 = 0.44$) in sustaining productive cassava-maize rotation system and improved soil quality within the semi-deciduous forest agro-ecological zone. It is thus, recommended that enhanced and targeted organic and inorganic fertilization regime could be deployed on the cassava-maize rotation system to improve the inherently low levels of nutrients and increase crop yields.

KEYWORDS

cassava, maize, semi-deciduous forest, soil fertility, soil quality, sustainability

1. Introduction

Cassava (*Manihot esculenta* Crantz) is a major staple food crop for over 800 million people in sub-Saharan Africa providing their calorie needs (Burns et al., 2010). It is the third most important source of calories next to rice and maize in tropical countries (Luar et al., 2018). Cassava also has the potential for use as an industrial raw material in the starch, alcohol and animal feed industries. The crop is regarded as a hardy crop, growing on marginal lands with little or no inputs, and it is usually planted as the last crop in any crop rotation cycle (Salami and Sangoyomi, 2013). Cassava is known to produce appreciable root yields in depleted soils where other crops would fail even though the crop removes substantial amounts of nutrients with the roots at harvest (Ayoola and Makinde, 2007). Despite the aforementioned, cassava production is constrained by several factors including low soil fertility, drought, and poor adoption of good agronomic practices leading to low root yields on croplands (El Sharkawy, 2007).

In Ghana, cassava is the lead starchy staple crop planted to over 900,000 hectares with an annual production of over 17.2 million metric tons (MT). Current average cassava yield is 18.73 MT ha^{-1} which is only 42 % of the potential yield of 45–50 MT ha^{-1} (MoFA-SRID, 2016). Such low root yields are attributed mainly to low soil fertility and poor land management.

Even though cassava is known to grow well on most soils, adequately well-drained soils that can retain enough moisture are quite ideal. Cassava, therefore, grows best on light to medium textured and well drained soils. The crop can thrive within a pH range of 4.5–7.5 but a range of 5.5–6.5 is more ideal. Cassava is a heavy feeder and therefore its nutrient removal from the soil for optimum yields is relatively high when compared to other root crops. Even though the crop is known to adapt to medium levels of soil N and P, it requires larger quantities of K, and more so when grown at a particular location over a longer period. On average, cassava extracts 4.9 kg N, 1.1 kg P and 5.8 kg K per ton of tuber harvested (Howeler, 1981).

Most often, the crop does not respond to mineral fertilizer applications when a virgin land or relatively fertile soils are cultivated. However, after a few years of continuous cultivation on the same piece of land, substantial P and K deficits are observed, particularly where soil erosion and leaching are quite high. Soil K is often the significant source of variation in yield after a few years cultivation in the absence of adequate and balanced fertilizer application. The crop also requires adequate levels of nutrients such as Ca, Mg, S and Zn for optimum root yields (Howeler, 1991).

This study was undertaken on the fields of JOSMA Agro-industries, a private and major cassava growing and processing company in the Ashanti region, located within the semi-deciduous forest agro-ecological zone of Ghana. JOSMA Agro-industries focuses on producing and processing cassava as their main activity. Over the years, a cassava-maize rotation system has been adopted on their croplands with mineral fertilizers applied to only the maize crop in the rotation. The purpose of applying mineral fertilizer is to ensure sustainable maize production, with the hope that the cassava crop, which follows the maize in the rotation, will benefit from the residual effect of the mineral fertilizer.

The present study was conducted to investigate the long-term effect of cassava - maize rotation on soil fertility status and soil quality of a *Gleyic Arenosol* in the semi deciduous forest zone of Ghana. Specifically, the study sought to (i) determine the current soil fertility status of the cassava-maize rotation, based on the different durations of cultivation, (ii) assess soil quality status (using Carbon Management Index as an indicator of soil quality) (iii) identify the most limiting nutrients and soil conditions affected by continuous cassava-maize rotation, and (iv) identify the most important soil properties that were influenced under the different crop-rotation systems, using principal component analysis.

2. Materials and methods

2.1. Characteristics of the study site

This study was undertaken on the fields of JOSMA Agro-industries, a private and major cassava growing and processing company in Ghana. JOSMA Agro-industries croplands are located at Woraso, near Ashanti Mampong in the Ashanti region, which lies between latitude 7° 07' and 7°12'N and longitude 1° 23' W, in the semi deciduous forest zone of Ghana. Annual temperatures are relatively high with a monthly mean of about 25.8°C.

The study area experiences equatorial climatic regime with two distinct rainy seasons with a mean annual rainfall of about 2390 mm in 294 rainy days (Figure 1). The major rainy season runs from April to July, during which over 75% of the annual rainfall may be received. The minor season occurs between September and November, followed by a long dry season from late November to early April (Figure 1).

The soils of the various parcels of croplands as described by Adu and Mensah Ansah (1995) are soils that have been developed over coarse-grained Voltaian Sandstone and classified as *Gleyic Arenosol.* In the natural state, the top soil is known to consist of 8–30 cm of dark brown, humus, loamy sand which grades downwards into a less humus dark brown to loamy sand. However, several years of cassava-maize rotation under regular deep plowing has transformed the top soils into brown loamy sands with no visible signs of dark brown color. Below the top soil at about 20 cm is yellowish red to reddish yellow sandy clay loam which is underlain by ironstone concretions from 60 to 80 cm depth. Even though the soils have been described as suitable for the production of cassava and maize, it has been suggested that higher doses of N, P, and K fertilization are needed for continuous and sustainable crop production (Adu and Mensah Ansah, 1995).

2.2. Crop management

Crop production activities were arranged in a Cassava - Maize rotation on all parcels of croplands. The recommended mineral fertilizer rate of 60:40:40 kg ha^{-1} of N-P_2O_5-K_2O was applied solely to the maize crop in the cassava-maize rotation. No organic or mineral fertilizers were consciously applied to the cassava crop.

Management staff of the farm were interviewed to assess the cropping systems that were adopted and the ages of the different parcels of croplands. The general description of the different parcels of cassava-maize plots are presented in Table 1. The lands were normally deeply-plowed using four-wheel tractors during land preparation before maize cultivation and later cassava was planted in the rotation. Mineral fertilizers, mainly NPK 15:15:15 and NPK 23:10:0, depending on their availability on the market, were applied to only the maize crop at a rate of 60-40-40 N-P_2O_5-K_2O kg ha^{-1}.

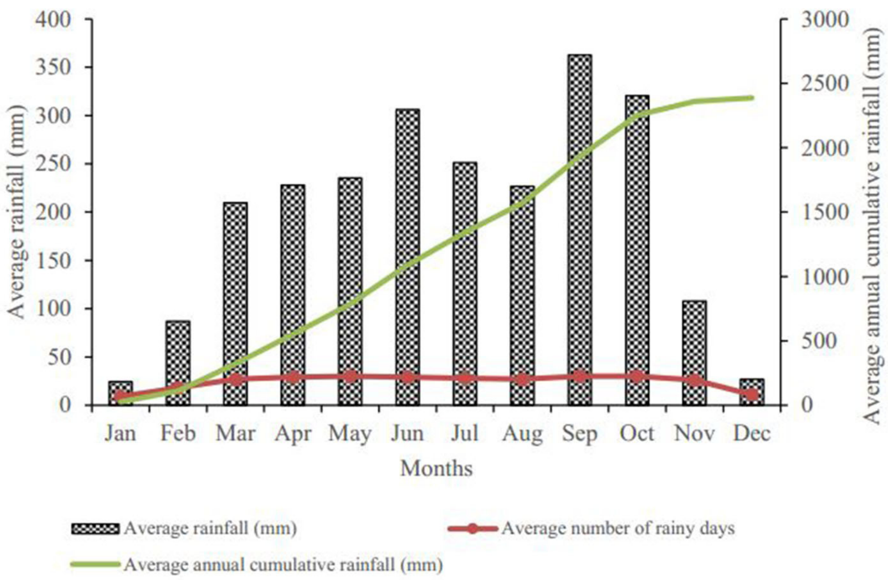

FIGURE 1
Average monthly rainfall amount and rainy days of the study site (2009–2021).

2.3. Soil sampling

Composite soil samples were collected at 0–20 cm and 20–50 cm soil depth from the different fields of cassava-maize rotation croplands for routine physico-chemical analysis using a soil auger. Soil sampling sites were selected in a manner so as to minimize soil variability from six spots on each field. In addition, composite soil samples were taken from an adjacent 14-year-old cashew plantation (Osei Kofi Lane) near the site for comparison. Soil samples were labeled and conveyed to the CSIR-Soil Research Institute laboratory for analysis.

TABLE 1 General description of the understudied croplands.

Site code	Description of fields	Years of continuous cropping	Rotation
ACP	Adjacent cashew plot	14	Cashew only (no rotation)
CMR 7	Agyakoma lane	7	Cassava/Maize
CMR 14	Osei kofi lane/bobin	14	Cassava/Maize
CMR 20	Palm Avenue Top parcel	20	Cassava/Maize

2.4. Laboratory analysis

Soil samples were air-dried, crushed and sieved through a 2 mm sieve before analysis. Soil pH was measured in 1:2.5 soil-water ratio using a glass electrode (H19017 Microprocessor) pH-meter (ASTM, 1995). Soil organic carbon was determined by the modified dichromate oxidation method of Walkley-Black as described by Nelson and Sommers (1982). Total nitrogen was determined by the Kjeldahl digestion and distillation procedure as described by Bremner and Mulveney (1982). Available Phosphorus was measured by the Bray 1 method as described by Bray and Kurtz (1945) while exchangeable bases (K, Ca, Mg, Na) were extracted in 1.0 *M* ammonium acetate (NH_4OAc) extract as described by Thomas (1982). Exchangeable calcium and magnesium were determined by EthylenediamineTetracetic Acid (EDTA) titration, whiles exchangeable potassium and sodium were determined by flame photometry. Exchangeable acidity was determined in 1.0 *M* KCl extract as described by Page et al. (1982). Effective cation exchange capacity was calculated as the sum of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) and exchangeable acidity ($Al^{3+} + H^+$). Particle size distribution was determined by the Bouyoucos hydrometer method as modified by Day (1965).

2.5. SQ determination

Soil quality was determined using Carbon Management Index (CMI) method, an assessment model that shows how a particular land use affects the soil quality relative to a reference land use soil (Blair et al., 1995). This technique is based on the premise that soil organic matter changes are gradual such that small changes are difficult to detect by conventional methods. It simulates the oxidative action of soil microbes by using 333 mM $KMnO_4$ to breakdown the readily decomposable organic compound known as labile carbon (Blair et al., 1995). The difference between the total organic carbon (Walkley–Black C) and the labile carbon gives the non-labile carbon which is that component of soil organic carbon that is likely to remain in the soil for relatively long periods. The resulting three soil C pools can therefore be used to initialize C cycling models (Blair et al., 1996).

TABLE 2 Particle size distribution of the various cropping systems.

Soil depth (cm)	Site /Plot	Sand	Silt	Clay	Textural class
		(g kg^{-1})			
0-20	ACP	880	60	60	Sand
	CMR 7	840	40	120	Loamy Sand
	CMR 14	880	20	100	Loamy Sand
	CMR 20	920	40	40	Sand
Mean		880	40	80	Loamy Sand
Standard deviation		32.66	16.33	36.51	
20-50	ACP	820	40	140	Sandy Loam
	CMR 7	740	40	220	Sandy Clay Loam
	CMR 14	780	40	180	Sandy Loam
	CMR20	720	60	160	Sandy Loam
Mean		765	45	175	Sandy Loam
Standard deviation		44.35	10	34.16	

Carbon Management Index was therefore determined as follows:

$$CMI = CPI \times LI \times 100 \tag{1}$$

where CPI is the Carbon Pool Index, and LI is the Lability Index of the soil under a particular land use (crop-rotation system),

$$CPI = \text{plot C stock/reference C stock} \tag{2}$$
$$LI = \text{plot C lability (L)/reference C lability} \tag{3}$$
$$L = \text{C stock in labile fraction (LF)/C stock in non-labile fraction (HF)} \ldots.. \tag{4}$$

2.6. Statistical analysis

The summary statistics of data collected from this study were determined using the Statistix 10 Windows statistical package. In addition to this, regression coefficients of studied soil nutrients with CMI on the different crop-rotation systems was computed. Also, an Eigen-vector based multivariate analysis, Principal Component Analysis (PCA), was used to extract the maximum variance in the data and identify the most important soil properties (variables) that were positively or negatively influenced by the different crop-rotation systems during the study period. Principal components were identified as the variables with Eigen value >1 and had a cumulative percentage variance of ≥ 80%. The with absolute loadings of ≥ 0.50 were identified as the significant variables contributing to each principal component.

3. Results and discussion

3.1. Soil texture

The soils are naturally deep with no gravels and concretions encountered within the 0–50 cm soil depth. The top soils (0–20cm) were observed to be sandy or sandy loam with an average particle size distribution of 880 ± 32.66 g kg^{-1} sand, 40 ± 16.33 g kg^{-1} silt and 80 ± 36.51 g kg^{-1} clay (Table 2). These soil textures are noted to have lower soil moisture and nutrient retention capacities for sustainable cassava production under such soil conditions, nutrient losses are expected to be very high particularly through leaching and erosion. These losses are enhanced by the effect of annual deep plowing using heavy equipment such as tractors. In addition, the sub-soils (20–50cm) of some plots have relatively higher levels of clay (160 – 220 ± 34.16 g kg^{-1}) (Table 2), which otherwise would have occurred below the 0–50 cm soil layer in the natural state (Adu and Mensah Ansah, 1995). This could limit root penetration and expansion under dry conditions and hence reduce cassava root yield. Continuous cassava cultivation has been reported to cause more soil loss through erosion due to regular deep plowing, wider spacing and slow initial crop growth thereby bringing the deeper non-desirable soil conditions, such as higher clay content, closer to the surface horizon. Such plowing could also possibly result in surface compaction for areas from the use of heavy machinery (Howeler, 2017a).

3.2. Soil fertility dynamics under continuous cassava-maize rotation

3.2.1. Soil pH

The pH of the topsoil (0–20 cm) ranged from 5.8 to 6.4 with a mean of 6.1 ± 0.23 while subsoil (20–50 cm) pH ranged from 5.7 to 6.4 with a mean of 6.1 ± 0.37 (Table 3). These pH levels are rated as moderately to slightly acidic (Loganathan, 1987) or medium (Howeler, 2017b) and are optimum for sustainable cassava production in the semi-deciduous forest agro-ecological zone. Topsoil pH was higher for all the different ages of cassava-maize rotation lands (CMR 7, CMR 14, and CMR 20) than the non-rotation adjacent cashew plot (ACP), though they were all moderately acidic. This is an indication that the disturbances of the topsoil associated with the continuous cassava-maize cropping particularly plowing and mineral fertilizer application helped to raise soil pH. However, sub-soil pH declined steadily with age (CMR 7 > CMR 14 > CMR 20), indicating possible increased acidity with age under continuous cassava-maize rotations. Soil pH reduction under continuous cropping with inorganic fertilizer application and constant deep plowing could be attributed to soil reaction associated with inorganic fertilizer use (based on type of fertilizer), accelerated soil erosion due to constant plowing and reduced soil organic matter accumulation on croplands as earlier observed by FAO and IFAD (2001).

3.2.2. Soil total nitrogen

Soil total N levels ranged from 0.7 to 0.9 g kg^{-1} for the topsoil (0–20 cm) with a mean value of 0.8 ± 0.10 g kg^{-1} and from 0.4

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TABLE 3 Soil nutrient dynamics within 0–20 cm and 20–50 cm soil depths under various cropping systems.

Soil depth (cm)	Cropping system	Soil pH (1:2.5 soil: water)	Total N (g kg^{-1})	Organic matter (g kg^{-1})	Available P (mg kg^{-1})	Exchangeable K ($cmol_{(+)}$ kg^{-1})
0–20	ACP	5.82	0.90	15.20	1.71	0.34
	CMR 7	6.37	0.80	12.10	2.51	0.14
	CMR 14	6.00	0.65	12.05	4.10	0.23
	CMR 20	6.15	0.80	13.30	1.68	0.25
Mean		6.09	0.79	13.16	2.50	0.24
Standard deviation		0.23	0.10	1.48	1.13	0.08
20–50	ACP	6.33	0.70	12.70	0.11	0.12
	CMR 7	6.43	0.40	8.20	0.11	0.31
	CMR 14	5.81	0.50	10.45	0.29	0.26
	CMR20	5.68	0.40	8.90	1.48	0.07
Mean		6.06	0.50	10.06	0.50	0.19
Standard deviation		0.37	0.14	1.99	0.66	0.11

TABLE 4 Exchangeable bases, acidity and ECEC levels under various cropping systems.

Soil depth (cm)	Site /Plot	Ca	Mg	Na	Acidity	ECEC
		cmol $_{(+)}$ kg^{-1}				
0–20	ACP	1.28	0.43	0.15	0.55	2.75
	CMR 7	3.20	0.85	0.12	0.15	4.46
	CMR 14	2.56	0.96	0.13	0.35	4.23
	CMR 20	2.56	0.85	0.09	0.20	3.95
	Mean	2.40	0.77	0.12	0.31	3.85
	Standard deviation	0.81	0.23	0.03	0.18	0.76
20-50	ACP	3.41	1.07	0.09	0.15	4.83
	CMR 7	2.34	1.28	0.10	0.10	4.12
	CMR 14	2.03	0.86	0.14	0.45	3.74
	CMR20	2.56	0.64	0.10	0.65	4.02
	Mean	2.59	0.96	0.11	0.34	4.18
	Standard deviation	0.59	0.28	0.02	0.26	0.46

TABLE 5 Effects of different cropping systems on carbon management index.

Site code	TOC (g kg^{-1})	LC (g kg^{-1})	CPI	L	LI	CPI*LI	CMI
ACP	8.80	1.31	1.00	0.17	1.00	1.00	100.00
CRM 7	7.00	0.76	0.80	0.12	0.70	0.55	55.39
CRM 14	7.00	0.63	0.80	0.10	0.57	0.45	44.98
CRM 20	7.70	0.59	0.88	0.08	0.47	0.42	41.51
Mean	7.63	0.82	0.87	0.12	0.69	0.61	60.47
Standard deviation	0.85	0.33	0.09	0.04	0.23	0.27	27.01

TOC, Total Organic Carbon; LC, Labile Carbon; CPI, Carbon Pool Index; L, Carbon stock in Labile fraction; LI, Lability index.

TABLE 6 Regression analysis of studied soil nutrients with CMI under various cropping systems.

Soil nutrients	Equation	R^2 value
pH	y = −72.67x + 502.67	0.39
Total N (g kg^{-1})	y = 196.91x - 94.594	0.57
Available P (g kg^{-1})	y = −10.51x + 86.738	0.19
Exchangeable K ($cmol_{(+)}$ kg^{-1})	y = 219.11x + 7.8855	0.44
Exchangeable Ca ($cmol_{(+)}$ kg^{-1})	y = −27.68x + 126.89	0.68
Exchangeable Mg ($cmol_{(+)}$ kg^{-1})	y = −111.30x + 146.45	0.93
ECEC ($cmol_{(+)}$ kg^{-1})	y = −31.31x + 180.92	0.78

TABLE 7 Principal component analysis for soil properties influenced by the different crop-rotation systems in the top soil (0–20 cm).

	Principal components		
	PC1	PC2	PC3
Eigen values	8.17	2.05	0.79
Variance (%)	**74.22**	**18.63**	**7.14**
Cumulative variance (%)	74.22	92.85	**99.99**
Soil pH	−0.29	−0.35	0.29
Total organic C	0.34	−0.13	−0.08
Organic matter	0.34	−0.14	−0.08
Total N	0.25	−0.45	0.30
Available P	−0.19	**0.59**	0.07
Exchangeable Ca	−0.34	−0.13	0.13
Exchangeable Mg	−0.33	0.12	−0.30
Exchangeable K	0.32	0.12	−0.40
Exchangeable Na	0.20	0.36	**0.73**
Exchangeable Acidity	0.31	0.34	0.05
ECEC	−0.35	0.01	0.03

PC, principal component; ECEC, effective cation exchange capacity. Bold values represent principal components.

to 0.7 g kg^{-1} for the subsoil (20–50 cm) with a mean of 0.5 ± 0.14 g kg^{-1} (Table 3). Total N levels for the topsoil and subsoil were < 1.0 g kg^{-1} and rated as low for sustainable maize and cassava production. The higher N level of 0.9 g kg^{-1} under the adjacent cashew plot (ACP) indicates that continuous cassava-maize cropping has resulted in a reduction of soil total N levels indicative of nutrient mining as mineral fertilizer additions may be either inadequate or unbalanced. Soil total N within the entire 0–50 cm soil depth varied with age of continuous cassava-maize rotation in the order ACP > CMR 7 > CMR 14 > CMR 20, indicating that continuous cassava-maize rotation led to reduced soil total Nitrogen with time, as all these were lower than the level recorded under the Adjacent Cashew Plot. Recorded levels of soil total N were far lower than the 1.2 g kg^{-1} reported by Adu and Mensah Ansah (1995) on a similar soil type under relatively stable natural vegetation. Thus, confirming that continuous cropping of

TABLE 8 Principal Component Analysis for soil properties influenced by the different crop-rotation systems in the sub-soil (20–50 cm).

	Principal components		
	PC1	PC2	PC3
Eigen values	5.61	3.53	1.86
Variance (%)	**50.99**	**32.11**	**16.90**
Cumulative variance (%)	50.99	83.10	**100.00**
Soil pH	0.33	−0.30	−0.18
Total organic C	0.31	0.27	0.33
Organic matter	0.30	0.27	0.35
Total N	0.36	0.21	0.27
Available P	−0.28	0.32	−0.31
Exchangeable Ca	0.34	0.27	−0.22
Exchangeable Mg	0.27	−0.41	−0.09
Exchangeable K	−0.02	**−0.50**	0.24
Exchangeable Na	−0.21	−0.05	**0.63**
Exchangeable Acidity	−0.34	0.32	0.05
ECEC	0.39	0.15	−0.22

PC, principal component; ECEC, effective cation exchange capacity. Bold values represent principal components.

any nature, regardless of the rotation type and age, leads to reduced soil total N.

3.2.3. Soil organic matter

Soil organic matter levels on all cassava-maize rotation fields were low for sustainable cassava production when compared to the classification of Howeler (2017b). Topsoil (0–20cm) levels ranged from 12.05 to 13.3 g kg^{-1} while subsoil (20–50cm) levels ranged from 8.2 to 12.7 g kg^{-1} (Table 3). Mean levels were 13.2 ± 1.48 g kg^{-1} and 10.1 ± 1.99 g kg^{-1} for the topsoil and subsoil, respectively. Soil organic matter levels on the cassava- maize rotation fields were all lower than the level under the ACP field which recorded levels of 15.2 and 12.7 g kg^{-1} for the topsoil and sub soil, respectively. This is an indication that continuous cassava-maize rotation resulted in SOM depletion, which could be due to a higher rate of decomposition (mineralization), and lower rate of accumulation (continuous removal of farm biomass) and erosion. Observed levels of soil organic matter for 0–20 cm soil depth was lower than the 18.0 g kg^{-1} reported by Adu and Mensah Ansah (1995) on a similar soil under relatively stable natural vegetative conditions. This confirms that continuous cassava-maize rotation leads to SOM depletion with possible adverse consequences on cropland productivity and soil carbon sequestration.

3.2.4. Soil available phosphorus

Soil available P (Bray 1) levels ranged from 1.68 to 4.1 mg kg^{-1} within the top soil and from 0.11 to 1.48 mg kg^{-1} within the sub soil (Table 3). Mean values were 2.50 ± 1.13 mg kg^{-1} and 0.5 ± 0.66 mg kg^{-1} for the topsoil and subsoil, respectively (Table 3). These levels are < 10 mg kg^{-1} the optimum available P levels (Loganathan,

1987) and rated as very low for sustainable and continuous crop production in the ecological zone. Topsoil available P levels increased gradually with time with the highest recorded under CMR 14, among all the other studied crop-rotation systems (including the ACP) indicating that cassava-maize rotation could have improved topsoil available P over time. The improvement in available P could, however, not be sustained beyond 14 years under the adopted land management regime. There was, however, a gradual improvement in available soil P levels with age of rotation within the subsoil (20–50 cm) with the oldest rotation period (20 years) recording the highest improvement of 1.48 mg kg^{-1}. This could be attributed to lower cassava P off-take and the residual effect of the continuous application of inorganic fertilizer to the maize crop. There is also the possibility of a highly effective symbiosis between the cassava and naturally occurring mycorrhizal fungi in the soil as reported by Howeler (2017b). The author explained that due to its coarse root system, cassava is highly dependent on Vesicular Arbuscular Mycorrhiza (VAM) for enhanced P uptake even under limiting soil P reserves to produce reasonable yield. This indicates that long term continuous cassava-maize production with some levels of mineral fertilizer application to the maize crop in the rotation, has the potential to enhance soil available P.

3.2.5. Soil exchangeable potassium

Mean exchangeable K levels for the topsoil (0–20cm) was 0.24 $\pm$ 0.08 $cmol_{(+)}$ kg^{-1} ranging from 0.14 to 0.25 $cmol_{(+)}$ kg^{-1} under the cassava-maize rotation plots (Table 3). These levels are lower than the 0.34 $cmol_{(+)}$ kg^{-1} recorded under the ACP plot within the 0–20 cm soil depth. This is an indication that continuous cassava-maize rotation decreased exchangeable K with time, even with the amounts of mineral fertilizer applied to the maize crop in the rotation. Mean subsoil exchangeable K was also 0.19 $\pm$ 0.11 $cmol_{(+)}$ kg^{-1} ranging from 0.07 to 0.31 $cmol_{(+)}$ kg^{-1} (Table 3). However, there was a gradual increase in soil exchangeable K with time within the subsoil for medium duration (7–14 years) rotations. Subsoil exchangeable K level was in the order: CMR7 > CMR 14 > CMR 20 indicating that continuous cassava – maize rotation reduced subsoil exchangeable K with time. This has the potential to lead to soil degradation if the current soil management regime is maintained. Even though the recorded mean soil exchangeable K levels are rated as medium for continuous cassava production (Howeler, 2017a), appropriate steps must be taken to improve these levels through fertilizer additions (organic/inorganic) to sustain higher levels of root yield such as cassava.

3.2.6. Other soil exchangeable cations

There were generally low levels of the other exchangeable cations (Ca, Mg, Na) across all cassava-maize rotation fields, leading to low effective cation exchange capacity (ECEC) levels (Table 4). Exchangeable Ca levels ranging from 1.28 to 3.41 $cmol_{(+)}$ kg^{-1}, was rated as low. According to Loganathan (1987), soils with exchangeable Ca levels < 5.0 $cmol_{(+)}$ kg^{-1} cannot support effective crop growth and will require fertilizer additions to improve levels. Similarly, exchangeable Mg levels ranged from 0.43 to 1.28 $cmol_{(+)}$ kg^{-1} which are also rated as low according to Loganathan (1987), as levels fall below the minimum 2.0 $cmol_{(+)}$ kg^{-1} required for effective root crop growth and optimum yields. Only exchangeable Na ranging from 0.09 – 1.15 $cmol_{(+)}$ kg^{-1} was rated as high according to Loganathan (1987) across all fields and at the various soil depths (Table 4). Loganathan (1987) further suggests that soils with ECEC levels <10 $cmol_{(+)}$ kg^{-1} cannot support or sustain cassava production unless adequate mineral fertilizer additions are made.

These results are also in agreement with the earlier observations of Sat and Deturck (1998) who reported that long-term cassava cultivation caused the most serious reduction in the ECEC, exchangeable K and Mg status compared with the long-term effect of forest, para rubber, cashew or sugarcane on the soil. In this study, continuous cassava-maize rotation had similar effect on ECEC, K and Mg compared to the adjacent cashew plot.

3.3. Soil quality dynamics

As shown in Table 5, the carbon management index (CMI), which was used as an indicator of soil quality, was highest in CMR7 and lowest in CMR20, as against the ACP (the reference land use type). CMI on the different aged cassava-maize rotation plots decreased greatly with the age, indicating that long term cassava-maize rotation reduced soil quality. This resulted in a sharper reduction of soil labile carbon (LC) fraction on the rotation plots with age, compared to the less severe reduction of TOC levels on the same plots (Table 4), indicating that continuous cassava-maize rotation led to more mineralization of soil organic matter compared to the adjacent cashew plot (ACP).

A similar observation was reported by Blair et al. (1996) that showed land use systems with high level disturbances such as regular plowing, accelerated TOC decomposition and hence LC reduction. In this study, continuous plowing, wider spacing of cassava, slow early cassava growth and associated inadequate mineral fertilizer use could have enhanced erosion and contributed to the reduction in both TOC and LC levels on the cassava-maize rotation plots and therefore affected the CMI, and hence soil quality. These observations are in line with the findings of Sainepo et al. (2018), who working on different land use patterns in Kenya, reported similar values of CMI on different land use types and confirmed that CMI could be used as a reliable indicator for soil degradation or improvement in response to land use and land cover changes.

3.4. Regression analysis among the soil nutrients with CMI

A regression analysis of some major soil nutrients and CMI revealed that pH, available P, exchangeable Ca, Mg and ECEC were negatively influenced by CMI whilst total N and exchangeable K were positively affected (Table 6). Total N and exchangeable K positively accounted for about 56.5 and 44.3%, respectively of the total variability in soil quality as measured by CMI. In addition, for every one unit increase of soil Total N, the CMI increases by 196.9 units, whilst for every one unit increase of exchangeable

K, the CMI increases by 219.1 units. This indicates that any soil management practice that lead to improvements or increases in soil total N and exchangeable K levels, can also lead to a better or improved soil quality and resilience for sustainable and continuous cassava-maize rotation.

These results are in line with the findings of Zanatta et al. (2019) who indicated that N fertilization was able to contribute about 8–33% improvement in soil quality better than no fertilizer under similar soil condition in Brazil. Furthermore, these results also corroborate with the findings of Adjei-Nsiah et al. (2007) who identified N and K as playing major roles in sustaining crops yield under cassava-maize rotation in Ghana.

3.5. Principal component analysis for the most important soil properties influenced by the different crop-rotation systems in this study

Results from the PCA of the soil properties, resulting Eigen values, individual percentage and cumulative variances in the topsoil (0–20 cm) and subsoil (20–50 cm) are presented in Tables 7, 8. For the topsoil, three principal components (PC1, PC2, PC3) were found to cumulatively explain approximately 99.99% of the variation in the soil properties among the crop rotation years. The soil properties which largely contributed to the variation in the topsoil were available P and exchangeable Na with Eigen vector scores of 0.59 and 0.73, respectively, as presented in Table 7.

Similarly, for the subsoil, three principal components were also found to cumulatively explain 100% of the variation in soil properties among the crop rotation years. These variations were largely contributed by exchangeable K and Na with absolute Eigen vector scores of 0.50 and 0.63, respectively (Table 8).

4. Conclusion

Long term cassava-maize rotations with inorganic fertilizer applied to only the maize crop leads to subsoil acidification. Such rotations also lead to significant reductions in SOM levels and soil nutrients such as total N, available P and the exchangeable bases (Ca, Mg, Na). As length of rotation period increased, levels of these nutrients continued to fall leading to nutrient mining and ultimately soil degradation. Even though levels of exchangeable K also decreased over the period with time, such reduction were quite minimal.

Soil Quality as measured by CMI declined with age under the continuous cassava-maize rotation indicating that the cropland management practices adopted by the landowners were not sustainable and lowered the resilience of the cropping system. As such, current nutrient management practices do not allow for nutrient build up. The use of compound fertilizer NPK: 23-10-0, that was sometimes used to fertilize the maize is neither good for maize nor cassava production because of the unbalanced nature of the nutrients and more importantly the very low levels of both P and K.

5. Recommendations

It is recommended that enhanced and targeted organic and inorganic fertilization regime could be deployed on the cropping system to improve the inherently low levels of exchangeable bases and increase crop yields. Soil management practices that improve SOM levels and enhance water and nutrient retention should be adopted. These may include the addition of farmyard manure, poultry droppings and legume rotations. The use of heavy farm machinery and deep plowing should be discouraged. Instead, light machinery supported by shallow plowing across the slope (direction of water flow) will reduce rapid erosion and minimize further degradation of the soil.

In addition, the cassava crop should be consciously fertilized using recommended mineral fertilizers. Maize should be fertilized using NPK 15-20-20 + Zn as recommended by the CSIR-Soil Research Institute. Good Agronomic Practices (GAP) that are recommended for Cassava and maize production must also be adopted.

Data availability statement

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

Author contributions

EOA, BEA, and MMB conceived the research, edited, revised, and made significant contributions. EOA and MMB planned the work. EOA, MMB, NB, and KA set up the experiment. EOA, BEA, NB, and KA collected and analyzed the data. EOA drafted 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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Solar-based irrigation systems as a game changer to improve agricultural practices in sub-Sahara Africa: A case study from Mali

Birhanu Zemadim Birhanu[1]*, Karamoko Sanogo[2], Souleymane Sidi Traore[3,4], Minh Thai[5] and Fred Kizito[6]

[1]International Crops Research Institute for the Semi-Arid Tropics, Dar es Salaam, Tanzania, [2]International Crops Research Institute for the Semi-Arid Tropics, Bamako, Mali, [3]Department of Geography, Faculty of History and the Geography, University of Social Sciences and Management of Bamako, Bamako, Mali, [4]GIS and Remote Sensing Laboratory, Institut d'Economie Rurale, Bamako, Mali, [5]International Water Management Institute, Accra, Ghana, [6]International Institute of Tropical Agriculture, Accra, Ghana

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EDITED BY
Jun He,
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Damodhara Rao Mailapalli,
Indian Institute of Technology Kharagpur, India
Zhang Yucui,
Chinese Academy of Sciences, China

*CORRESPONDENCE
Birhanu Zemadim Birhanu
✉ z.birhanu@cgiar.org;
✉ birhanuzem@yahoo.com

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Introduction: In rainfed agricultural systems, sustainable and efficient water management practices are key to improved agricultural productivity and natural resource management. The agricultural system in sub-Saharan Africa (SSA) relies heavily on the availability of rainfall. With the erratic and unreliable rainfall pattern associated with poor and fragile soils, agricultural productivity has remained very low over the years. Much of the SSA agricultural land has been degraded with low fertility as a result of ongoing cultivation and wind and water erosion. This has resulted in an increased food shortage due to the ever-increasing population and land degradation. Better agricultural and nutritional security are further hampered by the lack of reliable access to the available water resources in the subsurface hydrological system.

Methods: This study used socio-economic data from 112 farm households and Boolean and Fuzzy methods to understand farmers' perceptions and identify suitable areas to implement Solar Based Irrigation Systems (SBISs) in the agro-ecologies of Bougouni and Koutiala districts of southern Mali.

Results and discussion: Results revealed that the usage of SBISs has been recent (4.5 years), majorly (77%) constructed by donor-funded projects mainly for domestic water use and livestock (88%). With regards to irrigation, vegetable production was the dominant water use (60%) enabling rural farm households to gain over 40% of extra household income during the dry season. Results further showed that 4,274 km^2 (22%) of the total land area for the Bougouni district, and 1,722 km^2 (18%) of the Koutiala district are suitable for solar-based irrigation. The affordability of solar panels in many places makes SBISs to be an emerging climate-smart technology for most rural Malian populations.

KEYWORDS

climate-smart agriculture, farmers perception, irrigation, land suitability, solar energy, southern Mali, sustainable intensification, water management

1. Introduction

In many sub-Saharan African (SSA) countries, much of the agricultural development is constrained by the gap in knowledge on improved agricultural practices (Attia et al., 2022). This has resulted in few options for smallholder rural farm households to improve their livelihoods. The problem is aggravated by the increased frequency of rainfall variability and depleted soil nutrients from many of the farm fields. As a result, crop and livestock productivity has remained low for many years in most SSA countries (Birhanu et al., 2019). Much of the agricultural land in Mali has been degraded and is less fertile because of rigorous cultivation over the years along with wind and water erosion. This has resulted in increased food shortages as the land has not been able to support the food demands of the ever-increasing population. Better agricultural and nutritional security options are further hampered by the lack of reliable access to available water resources in the subsurface hydrological system. Sustainable and efficient water management practices are key to improved smallholders' agricultural productivity and natural resource management in rainfed agricultural systems.

Farmers in rural Mali cultivate vegetable gardens during the dry season using traditional irrigation systems. The vegetable gardens, though limited in scope, allow diversification of food in the household, leading to an increased household income. Traditional irrigation is practiced using shallow wells that have depths ranging from 6.5 to 14.5 meters (Birhanu and Tabo, 2016). A recently conducted survey on water availability and access in rural Mali revealed that while 39% of rural Malians always lack water, periodic water shortages are experienced by the majority of communities (61%) (Sanogo et al., 2021) sometimes or the other. In the traditional system, water for irrigation is collected manually from shallow wells through a bucket connected to a rope.

In recent years, several attempts are being undertaken in rural areas of developing countries (for example in Ethiopia, Senegal, and Ivory Coast) for the installation of electric pumps fed by solar energy and modern irrigation systems to promote renewable energy and water use efficiency in agriculture (Noubondieu et al., 2018). In Mali, despite developing institutional and programmatic commitments in 2011 (Attia et al., 2022), the government's ambitious plan to advance its irrigation capacity in the past decade was hampered by the worsening socio-economic and political crises. Additionally, there exists a huge potential investment gap in the Malian agricultural sector (Partey et al., 2018).

While it was commonly understood that SBISs are considered emerging climate-smart technologies (Noubondieu et al., 2018; Schmitter et al., 2018; Mugisha et al., 2021), little is known about their potential role in improving agricultural productivity for smallholders in Mali. In some parts of the country, farmers were better organized and were able to get support from different donor-funded projects. For example, the Feed the Future Innovation Lab for Small-Scale Irrigation (ILSSI), the CGIAR Research Program on Water, Land and Ecosystems (WLE), and the Africa Research In Sustainable Intensification for the Next Generation (Africa RISING) benefitted farmers for domestic water supply and small-scale irrigation practices (IITA and ILRI, 2018; Gadeberg, 2020). In their study of georeferencing 484 shallow wells in southern Mali, Birhanu and Tabo (2016) highlighted that the issue of water scarcity in most rural Mali was attributed to accessibility due to the lack of appropriate water-lifting mechanisms. Other studies (DNH, 2016) also confirmed that extraction and use of groundwater resources for irrigation have been very low in most places of rural Mali.

Of solar-based irrigation is promising for cost-effective and transformative technology to expand smallholder agriculture production, increase household water security, and offer solutions for climate-smart agricultural development (Brunet et al., 2018; Lefore et al., 2021; Xie et al., 2021). However, the expansion of solar-based irrigation is currently a hurdle for appropriate adoption due to the lack of integrated and adaptive approaches to address the contextual specification with diverse technologies, and actors across the public and private sectors (Ockwell et al., 2018; Minh et al., 2020; Izzi et al., 2021). Expanding SBISs, particularly in rural community settings require smallholder farmers' commitment and their increased awareness of the potential benefit of the investment. Similarly, a technical understanding of the environmental variables using available spatial and temporal data is important to establish criterion and restriction factors in identifying suitable sites to implement SBISs.

Recent studies employed a multiple-criteria-decision-making method and determined features such as accessibility to water sources, soil, slope, and land use and land cover (LULC) as important factors for surface irrigation site-suitability selection (e.g., Girma et al., 2020; Hagos et al., 2022). Similar spatial thematic layers and additional high-resolution datasets were collected and used in a mathematical algorithm in a GIS environment to facilitate the identification and selection of potential sites for SBISs in rural Mali (e.g., Kamaraju et al., 1996; Murthy, 2000; IWMI, 2019). Additionally, population density and data on urban and rural settlements were integrated into the machine learning algorithm to determine site suitability at the district level. A well-defined restriction factor was set for each data set using the Boolean model (Noorollahi et al., 2016) to aggregate the multiple factors and determine and select alternatives. Therefore, this study aimed to (i) understand farmers' perceptions and awareness of utilizing SBISs on the existing agricultural productivity and socio-economic benefits; and (ii) use a multiple-criteria-decision-making tool in a GIS environment to identify and map suitable areas for the potential investment of SBISs.

2. Materials and methods

2.1. Study area

The study was carried out in the Bougouni and Koutiala districts which comprise 41% of Sikasso's region in southern Mali (Figure 1). With a total land mass of 70, 280 km^2, rainfall in the region varies from 800 to 1,200 mm (Birhanu et al., 2022). Sikasso region, with a Sudanian savanna ecosystem (Cooper and West, 2017) inhabits a total population of 2.63 million (Institut National de la Statistique, 2009). The five other districts in the region include Kadiola, Kolendieba, Sikasso, Yanfolila, and Yorosso. The vegetation in the area is composed of wooded and shrub savannah which are well-preserved in the south but are severely degraded in

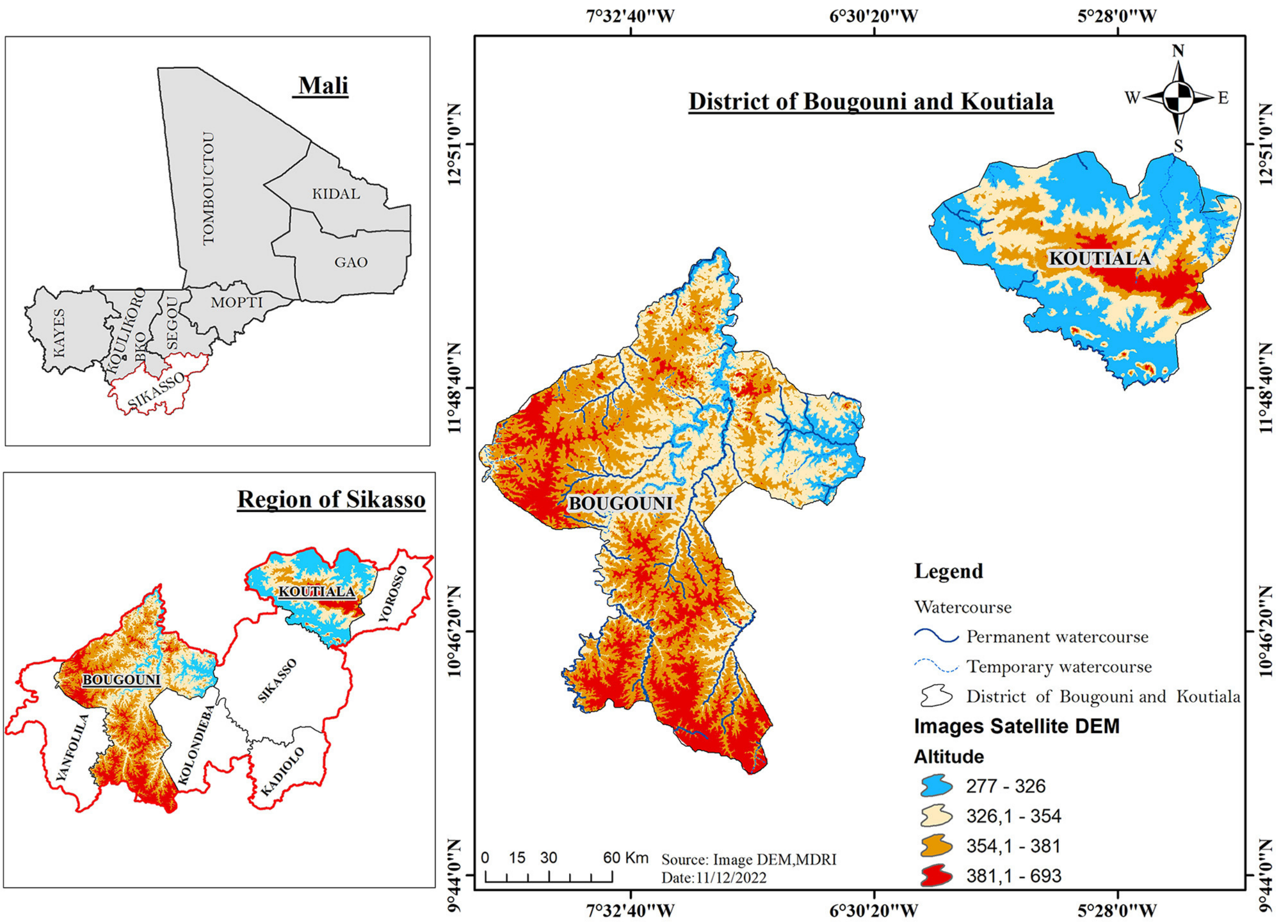

FIGURE 1
Study area Bougouni and Koutiala districts in the Sikasso region of southern Mali.

the center and the north of the districts. All the alluvial plains are covered with a grassy savannah and gallery forest along the rivers. The soils in the region are characterized as having high erosion risk, low water storage capacity, and poor drainage conditions. The agricultural economy in the region is characterized by rainfed, small-scale crops, livestock, and integrated crop-livestock/agro-pastoral farming systems (IITA, 2016). The months of June to September contribute 80% of the total annual rainfall. The long-term (1970–2018) mean annual rainfall of the Bougouni district is 1,060 mm, and that of Koutiala is 862 mm. The long-term (1970–2018) average monthly maximum and minimum air temperatures in the two districts are 33 and 22°C in Bougouni and 34 and 23°C in Koutiala, respectively (Birhanu et al., 2022).

2.2. Data and data source

Data for the study was collected from multiple sources (Table 1). Population data was sourced from the national census record. In this case, two population datasets were used. The first dataset was derived from the national demographic database of 2009 (Institut National de la Statistique, 2009). This dataset was used to estimate the population in 2019 INSTAT (2011). The second data was sourced from the World Population database available at 1 km resolution (Table 1). Spatial data on land use land cover and topographic variables were obtained at 30 m resolution from satellite-derived information using GIS and Remote Sensing tools. The soil map (1:500,000) of Mali was derived from the national Terrestrial Land Resources Inventories known as "*Project Inventaire des Resources Terrestre: PIRT*" of 1984. The world climatological database was used to derive the climate information required for the study. Environmental factors (land use and land cover, distance to urban/ rural areas) and economic factors (distance to the road, slope, distance to river, population density) were sourced from the Malian national GIS database available at the *Institute of Rulale Economy* (IER). Groundwater level data was sourced from previously georeferenced databases of Birhanu and Tabo (2016) and the spatial records of IWMI (2019). The collected spatial data at different scales were brought together using GIS software and re-scaled to make the output at a district level.

TABLE 1 Summary of data collected and data source.

Data	Variable	References	Resolution
Population	Population number	Institut National de la Statistique, 2009	District
	Population density	World population	1 km
Landsat 8 OLI	Land use and land cover	https://www.usgs.gov/landsat-missions/landsat-8	30 m
PIRT-Soil	Soil type mapping	PIRT, 1986	1:500,000
Aster-GDEM	Topographic variables	www.earthexplorer.org	30 m
Climate	Rainfall	www.worldclim.org	
	Average temperature		1 km
	Sunshine duration		
Environment	Land use and land cover	https://www.usgs.gov/landsat-missions/landsat-8	30 m
	Distance to urban/ rural areas	SotubaGIS database	–
Groundwater	Depth of wells	Birhanu and Tabo, 2016; IWMI, 2019	Village
Economic	Distance to road	SotubaGIS database	–
	Distance to river	SotubaGIS database	30 m
	Slope	Aster GDEM	30 m
	Population density	World population	100 m
Socio-economic	Household data	Survey	Village

2.3. Data analysis

2.3.1. Farmers perception

To understand farmers' perception and awareness of utilizing solar-based irrigation systems, gender-disaggregated socio-economic data were collected from a sample of 112 respondents (40 men and 72 women) in nine villages of the Bougouni and Koutiala districts. Descriptive statistics were applied to estimate the mean, maximum, minimum, and standard deviation of different variables such as respondents' age, level of education, farm size, period of using a solar-based irrigation system, and income of primary and secondary activities. Decision-making power at the household level to determine who decides the implementation of solar-based technologies and production income was assessed. The Chi-square test was used to determine the significant relationships among variables collected using SPSS software.

2.3.2. Soil

Soil type is an important input in identifying suitable areas for irrigation development in reference to its water-holding capacity and other associated physiochemical characteristics

TABLE 2 Area of dominant soils types in Bougouni and Koutiala districts.

Soils type	Bougouni	%	Koutiala	%
Entisols	0	0	3,356.20	35.53
Regosols	12,227.75	61.60	1,962.50	20.78
Lixisols	7,132.59	36.53	3,613.20	37.28
Gleysols	364.54	1.87	605.56	6.41
Total area	19,525.72	100	9,445.72	100

TABLE 3 Extent of LULC area in Km^2, for Bougouni and Koutiala district (2019 LULC data).

Land use land cover classes	Bougouni	%	Koutiala	%
Cropland	5,651.73	28.95	4,704.45	49.81
Dense vegetation	5,275.69	27.02	1,648.15	17.45
Low vegetation	6,895.57	35.32	2,487.65	25.26
Settlement	449.78	2.30	356.20	3.77
Bare land	1,049.78	5.38	246.03	2.60
Water bodies	203.18	1.04	3.24	0.03
Total	19,525.72	100	9,445.72	100

(Attia et al., 2022). The coarse-resolution PIRT composite soil map of 1:500,000 was downscaled into 1:200,000 using the Topographic Positioning Index (TPI) method developed by Jenness (2006). After downscaling, four soil types were identified in the Koutiala district with Lixisols as dominant (37.28%), while the dominant soil type in Bougouni was Regosols (61.60%) (Table 2).

2.3.3. Land use and land cover

From the 2019 land use and land cover data sourced from satellite imagery, six LULC classes were identified and later mapped after inferring with the ground truth data obtained from local extension agents, authors' know-how of the studied districts, and GIS specialists at the Institut d'Economie Rurale (IER). The major LULC class in both districts are *Low vegetation*, *Cropland,* and *Dense vegetation* (Table 3). Cultivation area accounts for nearly 30 and 50% of the total area for Bougouni and Koutiala districts, respectively. Between the years 1998 to 2019 population density increased by over 100% (i.e., from 16 to 32 inhabitants per km^2 for Bougouni, and 40–85 inhabitants per km^2 for Koutiala district).

2.3.4. Rainfall

Figure 2 depicts the isohyet distribution of mean annual rainfall in the two districts for the 1983–2021 period. The rainfall amount decreases from south to north and highlights a contrast between the two districts.

2.3.5. Slope

The slope is another important factor in selecting the optimal location for solar-based irrigation technology investment

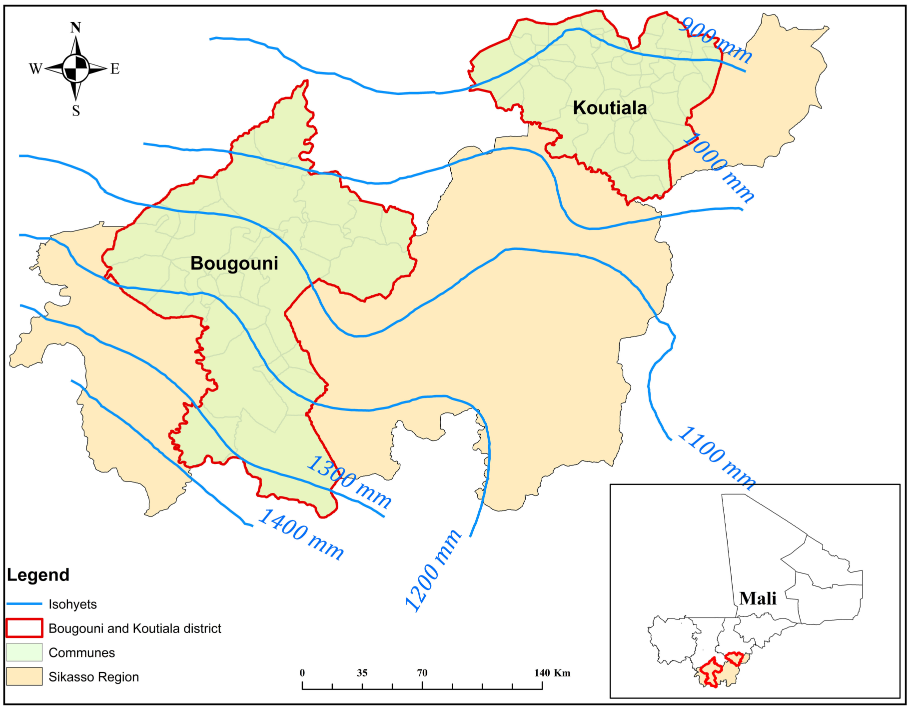

FIGURE 2
Mean annual rainfall (1983–2021) in southern Mali retrieved from ARC-2.

TABLE 4 Restriction factors for site selection using the Boolean model (based on literature and authors' understanding of the study area).

Parameter	Restriction layer	Unsuitable (value = 0)	Suitable (value = 1)
Slope	Slope percentage	X > 5%	X < 5%
Distance to river	Distance to seasonal and perennial rivers	X > 3 km	X < 3 km
Land use	Dense vegetation, low land, burn area, settlement, and water bodies	X < 100 m	X > 100 m
Population	Population density	X > 50 hbts/sqrkm	X < 50 hbts/sqrkm
Road	Distance to road	x > 10 km	x < 10 km
Urban/rural area	Distance to urban area	X > 5 km	X < 5 km
	Distance to rural area	X > 5 km	X < 5 km

as it directly influences the runoff-generating mechanism over catchments and recharging of aquifers (Carrillo et al., 2021). In addition, with increased land elevation, challenges related to accessibility arise and the potential for investment mainly in rural areas will be reduced (Zoghi et al., 2015). The higher slope of the surface leads to less recharging capacity in the below aquifers and leads to higher investment and operational costs. In the Boolean analysis, the lands with a slope of <5% were considered suitable (Table 4).

2.3.6. Urban/rural settlements

Building solar-based irrigation technologies closer to settlement areas affects future development and urban area expansion (Uyan, 2013). On the other hand, investment areas with long distances from residential areas are not economically feasible, the proximity to residential areas could be important (Zoghi et al., 2015). Therefore, areas with a distance >5 km were considered to be unsuitable for solar-based investments through the Boolean logic (Table 4).

2.3.7. Distance to roads

Proximity to roads has a better economic benefit for agricultural investments (Ma et al., 2005). Solar-based irrigation systems should not be built in areas with difficult access (Asakereh et al., 2014). Proximity to transport lines will reduce costs related to the operation, equipment loading, and personnel transport (Zoghi et al., 2015). The map layer related to this factor was created using a transport map of the study area. Land areas with a distance between 1 and 10 km from the roadside were considered to be suitable using the Boolean model (Table 4).

2.3.8. Distance to rivers

The distance to rivers is important because, in areas where rivers exist, recharging capacity and aquifer storage are high. Similarly, better access to surface water resources improves the economic feasibility of expanding the irrigation system (Paul et al., 2020). Attia et al. (2022) considered the Niger River as a base river in Mali in their mapping of land suitability at the national level.

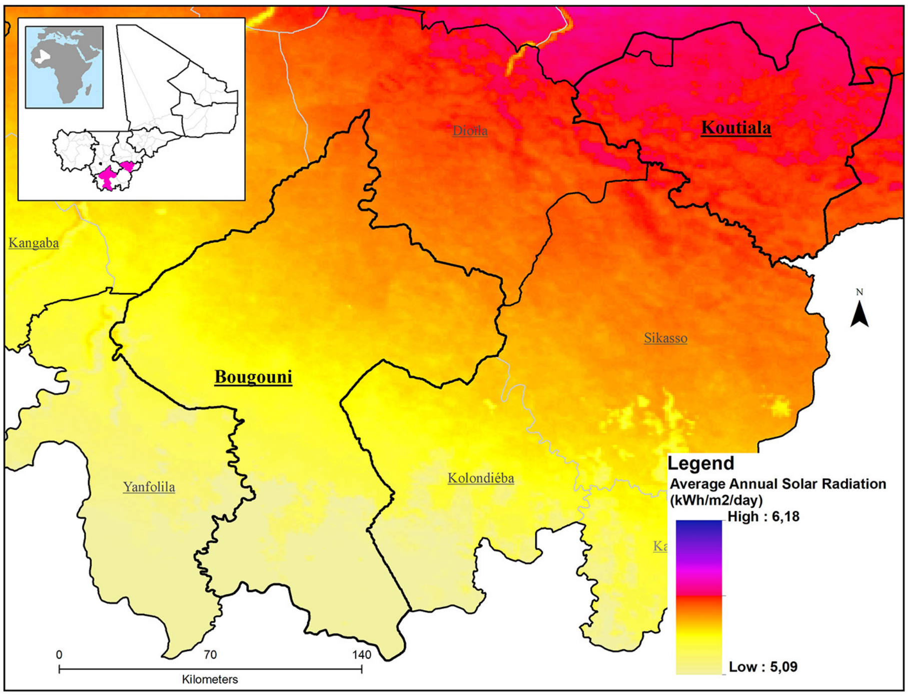

FIGURE 3
Average annual solar radiation map for the districts of Bougouni and Koutiala.

Other works, such as IWMI (2019) attempted to consider areas with <14 km from the nearby streams as suitable for irrigation development. In the present study, the distance to rivers map was built by buffering 200 m to 3 km from the stream networks as suitable areas using the Boolean model. This approach is very similar and in agreement with a recent publication by Negasa and Wakjira (2021) that stated land areas within a 10 km distance from surface water sources are highly suitable for irrigation development in most SSA catchments.

2.3.9. Solar irradiation

Solar energy-based installation sites must generate an adequate amount of energy to ensure their long-term viability for supporting the required demand. The amount of solar irradiation received on the earth's surface determines the amount of solar energy that can be converted to electricity. US National Renewable Energy Laboratory (NREL) classified values in kWh/m^2/day into four categories: moderate (<4), good (4–5), very good (5–6), and excellent (>6) (Phuangpornpitak and Tia, 2011). The solar irradiation map (Figure 3) retrieved from the World Climate database (Fick and Hijmans, 2017) showed that solar irradiation was between 5.08 and 6.18 kWh/m^2/day throughout the area in the two districts. The mean monthly sunshine duration computed from historical long-term data records (2000–2019) in both districts shows the highest and lowest sunshine durations in November (8.81 h) and August (6.93 h) respectively.

2.3.10. Integration of multiple inputs

A multiple-criteria-decision-making tool in a GIS environment was used to analyze and establish criterion and restriction factors in identifying suitable agricultural areas to implement SBISs. As an important step of the site selection criterion, a Boolean decision-making method as illustrated by Noorollahi et al. (2016) and Flora et al. (2021) was used to restrict sites that are not suitable to implement the technology (Table 4). Boolean logic converts information from each input raster map into binary forms of 0 and 1 (True or False). The excluded areas (restricted areas) were assigned a value of 0 while other areas (suitable areas) are assigned a value of 1 (Barakat et al., 2017). In the Boolean model (Flora et al., 2021), a land use map was used as a restriction factor to avoid: Dense vegetation, Water bodies, and Settlement areas, with a buffer of 100 m (Table 4). The maximum likelihood algorithm based on samples collected in Google Earth imagery and expert-based knowledge was used to extract the area of each identified LULC class using individual subset areas. The resulting map is a binary map because each location is either satisfactory or not (Shahabi et al., 2014). In the end, to prepare the final Boolean suitability map, an operator in a GIS toolbox was used to combine all layers to render the final product (Mattikalli et al., 1995; Zaidi et al., 2015) (Figures 4, 5). Model outputs at the district level were compared with previously published outputs that exist at the national level (IWMI, 2019; Attia et al., 2022). Knowledge of the study area was used as another validation option to determine the reliability of model outputs (Pramanik, 2016).

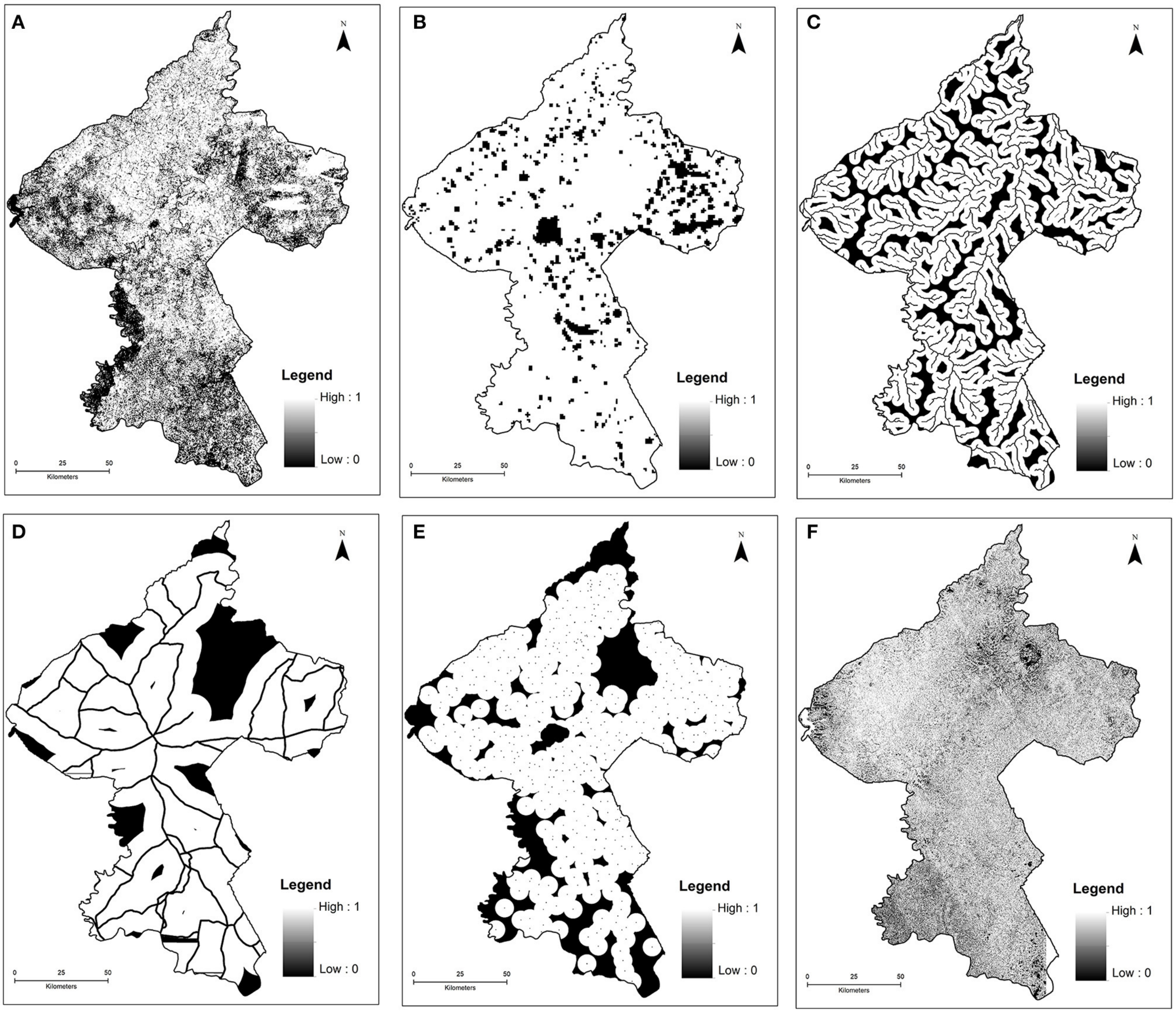

FIGURE 4
Restricted areas eliminated by Boolean Model (Bougouni district): **(A)** Land use land cover, **(B)** population density, **(C)** river network, **(D)** roads, **(E)** settlement, **(F)** slope.

3. Results

3.1. Agricultural practices using solar-based irrigation systems

The use of SBISs in rural Mali was recent, with a few years (4.5), and was on a limited land area (0.15 ha). Water was always available for household domestic use (60%), livestock water (28%), and irrigation (15 %). Female farmers are better users (64%) of irrigation systems mainly for vegetable production. The two main crops that farmers practice SBISs are Onion (49%) and Tomato (27%). Over the studied water sources in 112 farm fields, the depth of wells to irrigate vegetable crops vary from an average shallow well-depth of 19 meters to a deep well of 94 meters. The mean irrigation interval practiced by the majority of farmers (90%) was 14 h.

Water productivity according to farmers' perception was low. Summary statistics on water use and yield for major vegetable crops are shown in Table 5. The actual water use during the growing period was compared with the minimum water requirement published by the FAO database (Brouwer and Heibloem, 1986). For all crops, the actual amount of water applied was <50% of the required minimum amount. The majority of interviewed rural households (67%) however indicated they get sufficient water from wells for irrigation practices. Few farmers witnessed dryness of soil when the interval of irrigation exceeds 2 days, implying that irrigation practices were not following proper scheduling techniques. The yield obtained with farmers' irrigation technique was much less than the national average as well; 19.5 tons/ha for Onion, and 16.5 tons/ha for Tomato (FAOSTAT, 2020). While it was possible to get production data mainly yield (Table 5), data for stover yield of Onion, Pepper and Amaranth were not available,

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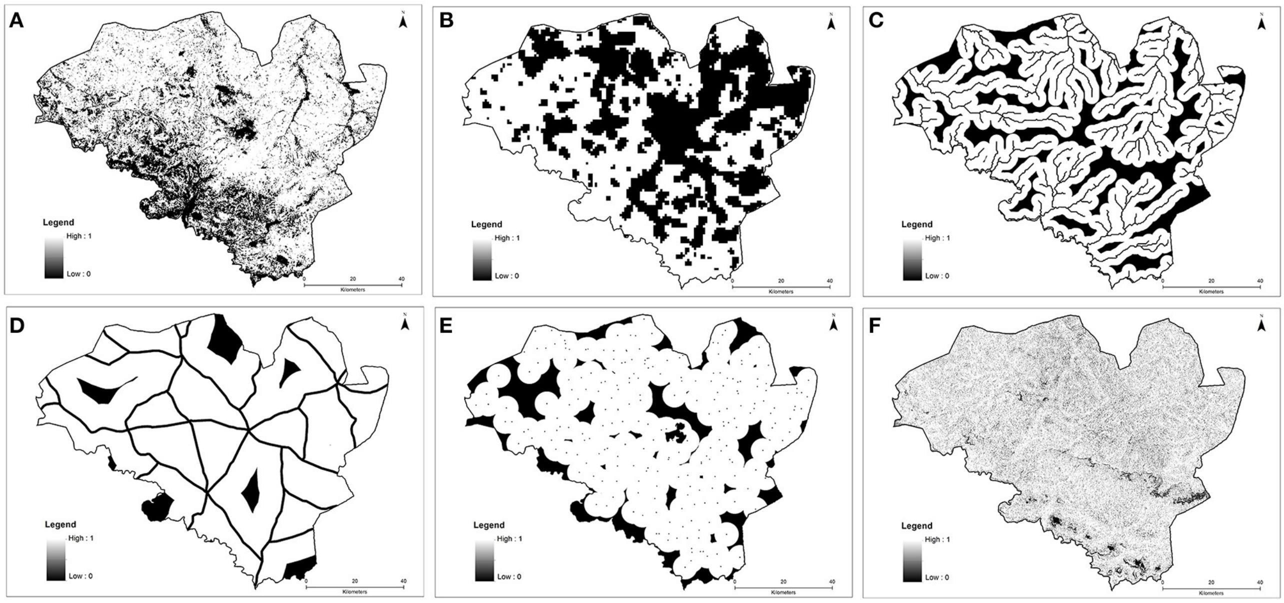

FIGURE 5
Restricted areas eliminated by Boolean Model (Bougouni district): **(A)** Landuse land cover, **(B)** population density, **(C)** river network, **(D)** roads, **(E)** settlement, **(F)** slope.

as the leaves of these crops were directly consumed by farmers at different times. The stover left from household consumption was used for livestock feed (73%) and the remaining manure was used to improve soil nutrients.

3.2. Socio-economics of implemented solar-based irrigation systems

Results of the socio-economic analysis revealed that the head of the household makes the majority of decisions about land ownership and the use of SBISs. Under the rural Malian context, household farmland belongs to the head of the family, which in the majority of cases (95%) is an adult male. Areas not under agriculture belong to the chief of the village who makes decisions on land allocation for various purposes including the implementation of SBISs. From a total of 112 farm households, the majority (65%) responded that vegetable production from the irrigation systems was controlled by the producer. The head of the household is the next person to control production. More than 56% of respondents highlighted that the producer decides on types of vegetable production. While few farmers (21%) directly fund the construction of the irrigation system on their farmland, project-initiated implementation of SBISs (77%) was established on the communal property with a decision that came from the village chief. Regarding awareness, communities are well-informed about the usefulness of SBISs. The majority (63%) responded that information comes from multi-stakeholder discussion forums and farmer-to-farmer interactions.

Over 50% of vegetables produced under SBISs are for sale. Pepper, African Eggplant, Tomato, and Okra are for sale in the majority of cases. Household consumption is relatively higher for Lettuce (59%), Onion (53%), and Amaranth (51%). With the available SBISs, the production of vegetables increased household income. The average income of each vegetable grower household during the dry season was \$56 (Tomato), \$60 (Onion), and \$69 (Pepper). The maximum sale value was \$175 (Tomato), and \$260 for the other two crops. Analyzed data further revealed that SBISs contributed over 40% of household income for 31% of the respondents. Eighteen percent indicated 30% of income from the sale of vegetable crops. Additionally, 14 and 15% of respondents indicated that solar irrigation system increased their income by 20 and 10%, respectively. For the other 22% of respondents, agricultural income increased by 5%.

The use of SBISs in rural Mali had challenges as well. Fifty-five percent of respondents noted that they lacked basic skills for maintenance work in case of faulty operations or breakage of part of the systems. It was also quite common to see conflicts arising mainly on the use of donor-funded installations on land provided by the village chief. Over 86% of respondents indicated that there are conflicts on the use of the SBISs. Conflicts arose mainly on the amount and timing of irrigation for different farms owned by different farmers. There are also disagreements on the service fee to be paid to a technician in case of systems component breakdown, and few users of the system were unwilling to make a monetary contribution toward replacing damaged parts. Respondents recommended the need to have appropriate training programs on the operation of the SBISs. In addition, guidelines related to water use and systems maintenance for long-term use were recommended to be developed at the village council level (see for example Umutoni and Ayantunde, 2018).

TABLE 5 Summary statistics on water productivity for main vegetable crops using solar energy in rural Mali.

Vegetable	N^*	Total water applied (during the growing period in mm)	Actual yield (tons/hectare)	Actual stover yield (tons/hectare)	Minimum water requirement [during the growing period in (mm)]	Potential yield (FAOSTAT, 2020) (tons/hectare)
Onion	57	168 ± 42	4.4 ± 3.7	ND	350	19.5
Tomato	50	60 ± 15	8.5 ± 7.5	0.51 ± 0.39	400	16.5
Pepper	32	56 ± 18	4.3 ± 4.1	ND	600	ND
Amaranth	15	29 ± 6.9	3.8 ± 3.7	ND	ND	ND
African Egg Plant	22	84 ± 20.4	5.8 ± 5.3	0.49 ± 0.42	ND	ND

N^*, number of data sampled; ND, no data.

TABLE 6 Area and percentage of suitable land for solar-based irrigation technology in Bougouni and Koutiala districts.

	Bougouni district		Koutiala district	
Landuse type	Area (km^2)	%	Area (km^2)	%
Suitable	4,274.24	21.89	1,722.16	18.23
Not suitable	15,251.48	78.11	7,723.56	81.77
Total	19,525.72	100	9,445.72	100

3.3. Land area suitable for solar-based irrigation systems

Quite a significant area of the landscape was found to be suitable for the implementation of SBISs in each district. Suitable land area was assessed using the Boolean method using various data sets. Land areas extracted from the combination of Boolean maps have been placed on the raster layers of fuzzy maps. Therefore, the unrestricted areas determined by Boolean overlay were evaluated by fuzzy functions. As shown in Table 6 and Figures 6, 7, nearly 22% of the land area in Bougouni is suitable to implement SBISs. The figure in Koutiala is 18%. In this study, the evaluation criteria were determined and categorized based on the authors' experience and reviews from the limited available information. In the context of Mali, communes are the lower administrative structure next to districts. Villages are clustered in each commune, as such the suitability maps of Figures 6, 7 show the location of villages, names, and boundary limits of each commune. As SBISs are implemented at the village level, each suitability map provides useful guidance to target villages. Villages located in the north, north-western and central parts of the Bougouni district and the eastern and southern parts of Koutiala are found to be suitable for the implementation of SBISs. These results confirmed the findings made at the national level by Attia et al. (2022) that for example in the Sikasso region suitable areas for irrigation development using solar energy are parts located in the northeastern and southern parts. With regards to land use management practices, areas identified as not suitable for SBISs can be reforested to prevent land degradation caused by soil erosion and hence enhance the ecosystem of the landscape by acting as aquifer recharging zones.

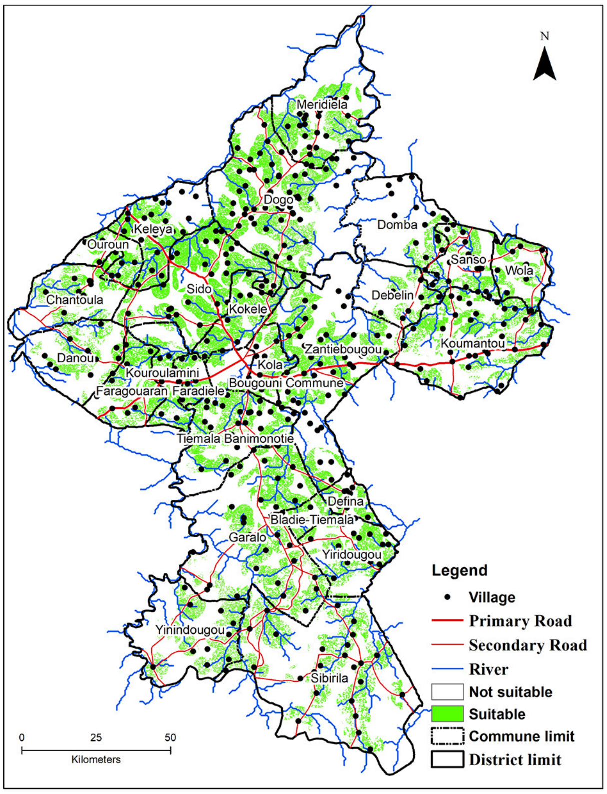

FIGURE 6
Final suitability map to implement solar-based irrigation system in Bougouni district.

4. Discussion

4.1. Prospects for SBISs development in Mali

The agricultural system in Mali heavily relies on rainfed agriculture which suffers from land degradation and a limited contribution from the small-scale irrigation system. Rising population growth and increased fragmentation of household farmland necessitate special and urgent attention to the use of CSA

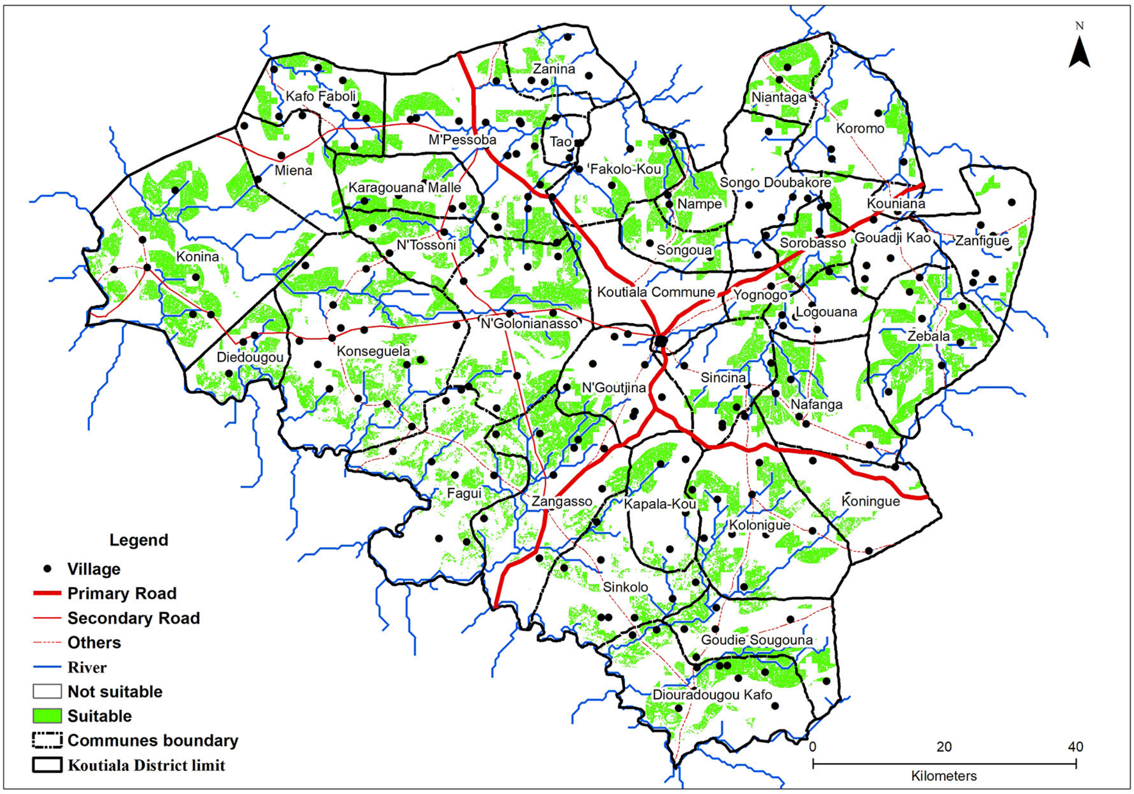

FIGURE 7
Final suitability map to implement solar-based irrigation system in Koutiala district.

practices that include SBISs (IWMI, 2019; Attia et al., 2022). In communities with large household sizes (for example the average in southern Mali is 27), increasing agricultural practices with irrigation-based technologies would ensure better household food security. Most rural Malians practice traditional irrigation systems except for a few donor-funded projects. Due to the limited water lifting systems and scarce availability of water in most shallow wells, the SBISs are practiced once a year in the majority of farm fields (69%).

Irrigation practices using solar energy are still considered by rural farmers as complementary to rainfed agriculture. However, the result of our study highlighted that ∼20% of the available land area in the two districts is suitable for solar-based irrigation investment. This potential, together with the untapped groundwater resource in Mali (Birhanu and Tabo, 2016), if properly managed and appropriate investments are in place, would be a game changer for the Malian agricultural system. Groundwater reserve in Mali is an untapped resource requiring due consideration along with other management practices in the changing climate condition.

Promotion and scaling of SBISs, however, are limited by the low rate of literacy level among most rural communities. The technology requires skills in implementation, maintenance, and use. However, 46% of the studied districts' rural communities do not have formal education (Sanogo et al., 2021). In situations when there are no industries or equivalent employers to provide local people with income-generating opportunities, the implementation of small-scale SBISs with the provision of required skills could be a useful option to enhance the livelihood of rural communities. This needs to include the introduction of low-cost soil water sensors that are useful to determine the minimum amount of water and frequency of irrigation (Adimassu et al., 2020; CSIRO, 2021).

The other limitation is the availability of suitable land. Land requirements, considered environmental factors, have been identified as one of the most critical factors for irrigation investments (Kahraman et al., 2009; Rabia et al., 2013). Despite being a major constraint in most developmental projects (Brewer et al., 2015), land use type is the foundation to plan and allocate land for diverse investment options (Tahri et al., 2015). For example, land with appropriate climate conditions for solar energy investments may have a lower value if the land use factor is taken into account (Carrión et al., 2008). Additionally, the dominant soil types in both districts, i.e., *Regosols* (in Bougouni), and *Lixisols* (in Koutiala) are characterized by low nutrient status and storage capacity and are susceptible to erosion. In this case, areas with Haplic Lixisols, Gleysols, and Ferric Luvisols were found to be suitable for solar-based irrigation development with the additional application of organic manure and mulches (Jalloh et al., 2011). In particular, Gleysols that are found in low-lying landscape positions with shallow groundwater reserves are better sites as they contain relatively higher organic matter and available nutrients (Jalloh et al., 2011).

Areas receiving annual rainfall >800 mm were found to be suitable as well. However, the spatial and temporal variability of rainfall as evidenced in southern Mali (Ebi et al., 2011; Akinseye et al., 2020; Sanogo et al., 2021) could be a limiting factor to recharge groundwater aquifers. This could also impact the sustainability of SBISs. As smallholder farmers cannot afford hydrocarbon-energized motor pumps or electrical pumps and the affordability of solar panels in many rural places as explained by Schmitter et al. (2018) makes SBISs to be an emerging climate-smart technology for most rural Malian populations. Hence, for a better result, the output of the study needs to be integrated with other intervention measures such as good agronomic practices (Traore et al., 2017) and landscape-based soil and water conservation practices (Traore and Birhanu, 2019; Birhanu et al., 2022).

4.2. SBISs as a game changer for smallholder agriculture in sub-Sahara Africa

In SSA, innovative irrigation systems are essential to secure smallholder farmers' year-round food production to contribute to the increased demand for food. SBISs are proven to potentially be a game changer for SSA smallholder agriculture from several aspects. SBISs are alternatives enabling smallholder farmers to grow more crops in a year by utilizing abundant sunlight and groundwater, mitigating climate change by reducing CO2 emissions (Brunet et al., 2018). SBISs can provide clean irrigation to millions of farmers, empowering their adaptive and resilient capacity by raising agricultural productivity and their incomes (Ockwell et al., 2018). SBISs can open new avenues of opportunity and potential for agricultural growth while transforming the entire range of farming systems in SSA.

Activating SBISs' game-changer potential, however, requires a long-term commitment and comprehensive ingenuity of thought and action, time, and determination across scales. Several attempts are being undertaken in SSA countries for the installation of electric pumps fed by solar energy and modern irrigation system to promote renewable energy and water use efficiency in agriculture (Noubondieu et al., 2018; Mugisha et al., 2021). Investments in west African countries (e.g., Ghana, Senegal, Mali, Gambia) focus on multiple initiatives for testing, de-risking, subsidizing, and analyzing policy reform to sustainably scale solar-powered pumps (Brunet et al., 2018; Lefore et al., 2021). SBISs as game-changer must have the ability to manage uncertainties and overcome obstacles. Enabling this ability requires adaptive approaches to overcome systemic barriers related to the lack of contextually relevant innovation bundles, appropriate end-user financing, policy frameworks biased toward large-scale irrigation and rain-fed agriculture, weak market linkages, nascent private sector investment and increasing competition for water among sectors (IWMI, 2021a). It also needs to integrate public, research, and private sector actors to respond to diverse incentives and environmental trade-offs with the underground water depletion and e-wastes (Minh et al., 2020; Lefore et al., 2021) and improve stakeholder coordination, enact more effective policies, and facilitate integration within the value chains and across sectors (Izzi et al., 2021).

In the case of Mali, enabling SBISs as a game-changer is driven by viable business and investment opportunities, appropriate finance tools, and market integration for solar entrepreneurs and irrigators. There is a growing presence of private sector solar technologies suppliers but the solar technology market can grow to reach many farmers directly when the demand for and supply of SBISs are matched. Understanding the diversity of farmers' SBISs demands, coupled with the solar irrigation suitability map (IWMI, 2021b) helps the suppliers to prioritize geographical areas for their marketing activities and business investments.

Farmers' demands are different in terms of the amount of water needed, land and water access, pump preferences, and capacity to pay for the SBISs. Tailoring the supply business models to different demands and abilities to invest is one of the necessary conditions to unpack the market bottlenecks. For example, in the areas where resource-limited and resource-poor farmers can access shallow groundwater like in areas of Dogo, Kokele, and Sibirila of Bougouni district, and N'golonianasso and M'Pessoba communes of Koutiala district, the business models should focus on supplying the solar-powered pumps with low capacity to match these farmers' ability to invest.

Finally, accelerating the SBISs requires an enabling environment in which domestic manufacturers, irrigation and input suppliers, and small processing businesses can grow. Sustainable financing models help de-risk private sector investments in irrigation markets, especially products and services that support gender and youth inclusion. Win-win partnerships between entrepreneurs, farmer groups, cooperatives, and private and public sector actors help optimize the engagement of private sector companies that supply different equipment along the continuum of agricultural water management, creating a more robust irrigation market for farmers. Multi-stakeholder dialogues and platforms are ways to engage diverse business actors to increase market density and integration (Minh et al., 2020). They also encourage collaboration and learning to drive responsive innovations to address social and gender inequality, economic empowerment, water governance, and multi-sector/stakeholder coordination to accommodate local contexts, diverse partners and stakeholders, and emerging needs for feasible and sustainable SBISs (Lefore et al., 2021).

5. Conclusions and recommendations

The study focused on the understanding of irrigation practices based on farmers' perceptions, and the identification of suitable areas for solar-based irrigation systems in the districts of Bougouni and Koutiala of southern Mali. Multi-criteria-decision-making approach was employed in a Geographical Information System (GIS) environment to provide spatial information on areas suitable for solar-based irrigation systems. With the limited available data, this study demonstrated, the investment in solar-based irrigation systems brought improvements in enhancing socio-economic status and reduction in economic vulnerabilities. In each district, nearly one-fifth of the landscape is suitable for the installation of solar-based irrigation systems. The generated suitability maps of the districts provide needed input to support planning and sustainable implementation of low-cost solar-based irrigation systems as a climate-smart technology. For sustainable agricultural development in rural economies, the results of the study need to be integrated with improved agronomic management practices and landscape-based soil and water conservation techniques. Additionally creating an enabling environment that facilitates sustainable financing mechanisms helps to support gender and youth inclusion in the use of solar-based irrigation systems. The findings of the study would benefit further from an investigation on a cost-benefit analysis that helps to promote the uptake of the technology by an ordinary rural farmer. Training programs on the operationalization of the system and the development of guidelines on water use and system maintenance are necessary criteria to ensure long-term usage and scale the technology in wider suitable landscapes.

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

BB and KS designed the study outline beginning with defining the objectives and identifying the different data requirements. ST contributed to the spatial data collection and analysis. KS administered socio-economic data and conducted the analysis. BB, KS, and ST contributed to the analysis and interpretation of socio-economic and spatial data. MT contributed to the discussion section of the manuscript. The manuscript was written by BB. A content revision was provided by FK. All authors have read and accepted the final version of the manuscript.

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Conflict of interest

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

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EDITED BY
Benjamin Karikari,
University for Development Studies, Ghana

REVIEWED BY
Derek Byerlee,
International Food Policy Research Institute, United States
David Butler,
The University of Tennessee, Knoxville, United States

*CORRESPONDENCE
Zuwena J. Ngoya
jacksonz@nm-aist.ac.tz;
zuwenajackson@yahoo.com

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Understanding farmer knowledge and site factors in relation to soil-borne pests and pathogens to support agroecological intensification of smallholder bean production systems

Zuwena J. Ngoya[1,2]*, Angela G. Mkindi[1], Steven J. Vanek[3], Patrick A. Ndakidemi[1], Philip C. Stevenson[4,5] and Steven R. Belmain[4]

[1]Department of Sustainable Agriculture, Biodiversity and Ecosystem Management, The Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania, [2]Department of Agronomy, Mwalimu Julius K. Nyerere University of Agriculture and Technology, Mara, Tanzania, [3]Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, United States, [4]Department of Agriculture, Health and Environment, Natural Resources Institute, University of Greenwich, Kent, United Kingdom, [5]Royal Botanic Gardens, Kew, Richmond, United Kingdom

Introduction: Pests and diseases limit common bean (*Phaseolus vulgaris*) production in intensifying smallholder farming systems of sub-Saharan Africa. Soil-borne pests and diseases (SPD) are particularly challenging for farmers to distinguish and manage in cropping systems that vary in terms of soils, farmer knowledge, and management factors. Few studies have examined soil drivers of SPD in smallholder systems, integrated with farmers' perceptions and management practices.

Methods: In Kilimanjaro, Tanzania, we assessed farmer knowledge and SPD management for common bean alongside soil type and soil quality. Focus group discussions and field survey findings including farmer observations and soil nutrient balances were integrated with soil analyses of farmers' fields. Multiple correspondence analysis (MCA) and principal component analysis (PCA) assessed relationships among farmer demographics, pests and diseases, soil characteristics, and management practices.

Results and discussion: Surveys revealed that 100% of farmers knew of the bean foliage beetle (*Ootheca bennigseni*) but few recognized the soilborne pest *Ophiomyia* spp. or bean fly despite it being more destructive. About a third of farmers knew of root rot diseases caused by *Pythium* spp. and *Fusarium* spp. Synthetic pesticides were used by 72% of farmers to control pests, while about half that (37%) used pesticidal plants, particularly *Tephrosia vogelii* extracts sprayed on foliage. Regarding SPD, 90% of farmers reported that their management practices were ineffective. Meanwhile, synthetic fertilizers were used by nearly all farmers in beans intercropped with maize (*Zea mays*), whilst very few farmers used manure or compost. Soil available phosphorus was lowbut showed a balance between inputs and outputs regardless of whether fields were owned. Field nitrogen balances were more negative when fields were owned by farmers. An MCA showed that older farmers employed a greater number of pest control practices. The PCA showed that field variability was dominated by soil organic matter, elevation, and soil pH. Higher organic matter levels were also associated with less stunting and wilting of beans observed by farmers. Our results suggest that research and farmer learning about SPD ecology are key gaps, alongside recycling of organic residues to soils. Cost-effective and sustainable practices to manage bean SPDs for smallholders are also needed.

KEYWORDS

pesticidal plant, botanical pesticide, *Fusarium* spp., *Pythium* spp., *Phaseolus vulgaris*

1. Introduction

Smallholder farmers producing common bean (*Phaseolus vulgaris* L.) are constrained by a number of challenges, including diseases, insect pests and poor soil fertility, which can result in severe yield losses in Tanzania (Hillocks et al., 2006; Nassary et al., 2020). Insect pests and diseases are ranked first in causing losses and these can reach 60% in common bean in Tanzania (Ronner and Giller, 2013) and up to 100% crop loss when no control measures are taken (Laizer et al., 2019). Pests and diseases affecting leaves and pods are generally recognized and managed by farmers (Stevenson and Belmain, 2017). However, soilborne pests and diseases (SPD) are often neglected in common bean production due to poor knowledge of causal agents, or the attribution of belowground damage to above-ground pests and diseases (Sekamatte and Okwakol, 2007). Farmers neglect SPD because they are not aware of the feeding habit of soil-borne insects and the damage caused by soil-borne pathogens. Three bean fly species *Ophiomyia phaseoli* (Tryon), *Ophiomyia spencerella* (Greathead) and *Ophiomyia centrosematis* (DeMeijere), and bean foliage beetle (*Ootheca bennigseni*) are the most important insect pests at the germination and seedling stages of common bean (Buruchara et al., 2010). Previously published studies on the larva of bean fly which is referred to as "bean stem maggot" shows that the pest status and management are poorly understood among farmers (Laizer et al., 2019). For example, bean fly and bean foliage beetle larval feeding activity cause above-ground symptoms from nutrient deficiency in common bean plants, affecting root growth and nutrient transport (Schwartz and Pastor-Corrales, 1989). Hence, if neglected, these pests can seriously damage common bean seedlings leading to 33–100% crop loss for bean flies (Karel and Ashimogo, 1991; Abate and Ampofo, 1996) and 18–30% crop losses by bean foliage beetle larvae in the soil in Tanzania (Abate and Ampofo, 1996). Poorly recognized soil-borne fungal diseases in common bean include root rot which can be caused by a variety of fungi including species from the genera of *Rhizoctonia, Pythium, Fusarium, Sclerotium*, and *Macrophomina* (Rusuku et al., 1997; Buruchara et al., 2010). Root rot fungi attack the root or crown region of the stem of the host plant (Sekamatte and Okwakol, 2007) causing damping-off, seed rot at the pre-germination, germination stage or even after germination, restricting water and nutrient uptake (Valenciano et al., 2006) leading to 70% yield loss (Papias et al., 2016; Mwaipopo et al., 2017). Laizer et al. (2019) indicated that farmers rank field insect pests as the major constraint leading to common bean yield loss followed by weeds, whereas crop diseases are least reported.

Huber et al. (2011) reported that plants with optimum nutrient supply grow more vigorously and enable a plant to have a higher capacity to compensate for pathogen infection and insect feeding. Symptoms of nutrient deficiency in plants may be caused by bean fly and bean foliage beetle larval feeding activity (Schwartz and Pastor-Corrales, 1989), which impairs root growth and nutrient transport (Huber et al., 2011) while poor soil fertility can also exacerbate the severity of insect attack (Hillocks et al., 2006). However, the application of excess inorganic N can increase amino acid concentrations which influences the penetration and growth of fungal hypha (Huber et al., 2011) and increased bean fly (O. *spencerella)* infestation (Letourneau, 1994). Bean fly and bean foliage beetle infestation are further aggravated by the presence of soil-borne pathogens such as *Fusarium* spp. and *Pythium* spp. root rots (Buruchara et al., 2010) where the insects take advantage of fungal damage to enter into the plant roots and stem (Schwartz and Pastor-Corrales, 1989).

A common control method used for the management of SPD is synthetic pesticides (Mahmood et al., 2017). However, their use by smallholder farmers is limited by high cost (Abate et al., 2000), and their misuse results in considerable human and environmental health problems (Stevenson and Belmain, 2017). There is renewed interest in the use of pesticidal plants along with soil health improvement to better manage insect pests and diseases (Belmain et al., 2022). Common bean smallholder farmers in our study area use pesticidal plants for controlling insect pests and diseases, mainly targeting above-ground pests and diseases (Mkindi et al., 2021) as there is little evidence of the use and efficacy of such products on below-ground pests and pathogens (Toepfer et al., 2021). Further, more needs to be known in African smallholder systems on how soil type, soil quality and farmer management of soil health and fertility contribute to SPD, although studies from other areas show some promising findings (Watson et al., 2002; Janvier et al., 2007; Birkhofer et al., 2008; Huber et al., 2011). Therefore, the purpose of this study was to explore the knowledge of and perceptions of damage from SPD, as well as local management strategies, in relation to soil type and soil fertility. We also sought to explore these factors along an elevation gradient of smallholders' bean fields near Mount Kilimanjaro, Tanzania. Furthermore, the study related these knowledge and management aspects, including the use of pesticidal plants, in a smallholder community setting with different livestock herd sizes, field sizes and land ownership parameters.

2. Materials and methods

2.1. Study site

The study was conducted on the slopes of Mount Kilimanjaro along an elevation gradient in smallholder farming communities in Hai District (latitude −3.232 to −3.384 S and longitude 37.238

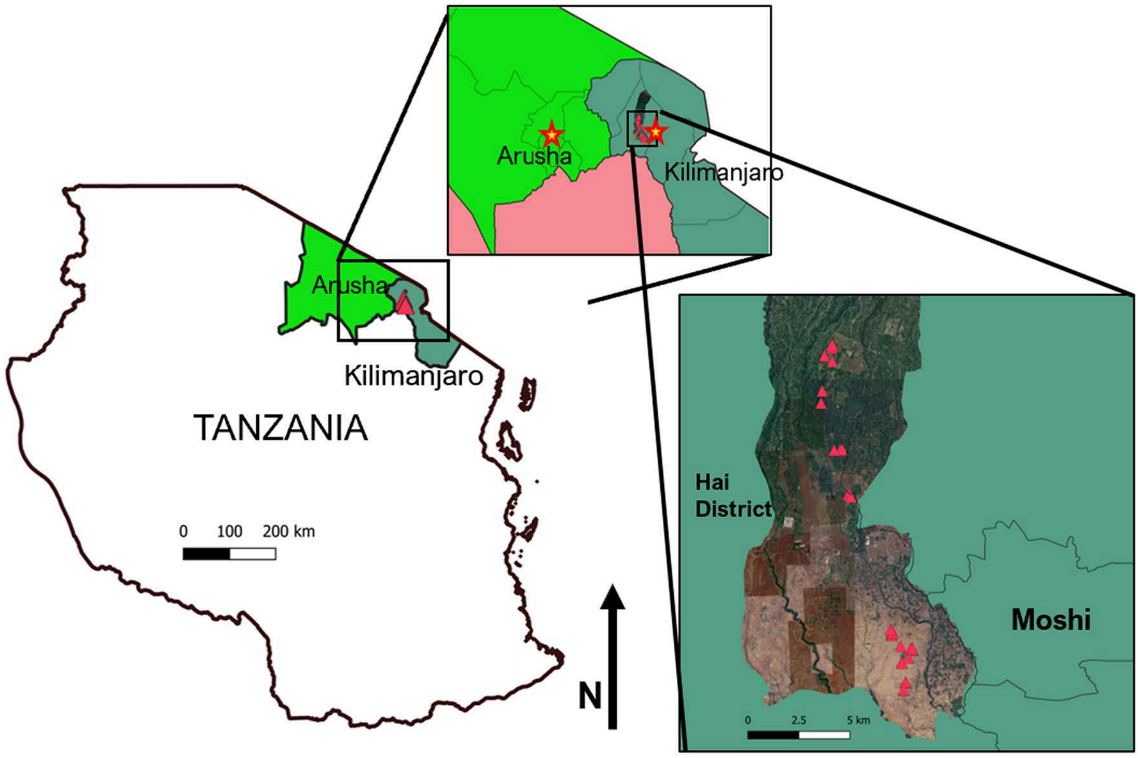

FIGURE 1
Study location indicating farmers' fields in the Hai District of the Kilimanjaro Region of northern Tanzania, where farm-level questionnaire surveys were conducted. Survey fields were arranged along an elevation gradient on the lower slopes of Mt. Kilimanjaro.

to 37.281 E; Figure 1). Permission to carry out the research was granted by the district council and community-based officials, with all farmers involved providing their consent. The study was done under the Farmer Research Network (FRN) project with an official research permit from the Tanzania Commission for Science and Technology (2021-181-NA-2021-061). The annual temperature ranges from 15 to 30°C, with a mean annual rainfall ranging from 500 mm in the lowlands and 2,000 mm in the highlands. Rainfall is bimodal with a long rainfall season from March to June and a short rainfall season from November to December. Altitude ranges from 700 to 1,500 meters above sea level (m.a.s.l) (Lema et al., 2014). Soils in the higher elevations are Acrisols (https://soilgrids.org/) (extracted study area map in Supplementary Figure 1) which have low base cation status, low activity clay on topsoil, and more organic matter (FAO, 2006). Soils in the middle elevations are ferralsols with good physical properties and poor chemical fertility having relatively weak cation retention capacity (Massawe and Mrema, 2017). Soils in the lower elevation are chromic luvisols having high base status and low activity clay on topsoil (FAO, 2006). Farming practices in the area consist of smallholder agriculture where most farmers practice intercropping of maize and beans. Other crops grown include bananas, coffee and leafy vegetables. Common beans are often grown as a mono-crop during the short rain season and as an intercrop with maize in the long rain season and have been grown in the region for several decades. Farmers in higher and middle elevations grow common bean on rented land or in small pieces of land around their homestead while most farmers in the lower elevations own larger farm fields.

2.2. Focus groups and interviews with farmers

Farmer's knowledge, attitudes, and practices with regard to bean cropping and particularly SPD were collected in the Narumu Ward of Hai District. Focus group discussions (FGD) with 64 farmers within eight different groups were facilitated with the assistance of village extension officers and research assistants involving farmer representatives nominated by farmers in different areas. Eight participants were selected for each focus group in a purposive way to cover a wide possible range of experience and knowledge in common bean production. Preliminary information on the level of farmer knowledge and their local taxonomy of SPD were collected. Farmers' observations and knowledge of field disease symptoms and insect damage were also recorded. The discussions allowed farmers to share their knowledge and experiences regarding SPD and their management practices including synthetic and pesticidal plants use. General guiding questions were used, and provoking questions were asked when necessary (questions available in online Supplementary material 1). Topics discussed included knowledge on common bean production, SPD, use of pesticidal plants and other practices for controlling pests and diseases, constraints to their control as well as methods observed to be successful by farmers in managing SPD.

A farm-level, individual questionnaire survey was also carried out to capture farmer demographic information as well as their knowledge of bean fly, foliage beetle and root rot disease damage, and management practices including pesticidal plant use practices. A total of 54 common bean farmers were interviewed individually. Some participants in the farm-level questionnaire were also involved in the FGDs but new participants were included who did not have experience in using pesticidal plants to control insect pests and diseases. To provide clear references for the responses and observations of pest incidence in the field, live insects were shown to farmers to see the color and size of insect pests. Also, damaged plants showing feeding or oviposition behavior of bean fly and bean foliage beetle were displayed before starting the interview. Questions for the farm-level individual questionnaire were prepared using Kobo Toolbox (https://kf.kobotoolbox.org/) and data were collected using smartphones with Open Data Kit (ODK) open-source mobile data collection software (https://opendatakit.org/). The questionnaires were pre-tested in a pilot study before being used by the targeted respondents.

2.3. Assessment of soil nutrient and management by farmers

Farmer practices with respect to soil fertility management were collected in individual discussions in farmer fields with the same 54 farmers involved in questionnaires about pest and disease management. Information on livestock keeping, herd sizes, land ownership and soil management was collected as part of a nutrient balance survey. A partial nutrient balance reflecting nutrient inputs, harvests, and estimated nitrogen (N) fixation was adapted from the NUTMON framework and previous nutrient balance assessments in smallholder systems (Smaling and Fresco, 1993; Ampofo et al., 1998; Vanek and Drinkwater, 2013; Nyamasoka-Magonziwa et al., 2020). The nutrient balance information on field size, crop type, harvests, and types and amounts of manure, fertilizer, and other inputs were gathered using a second survey implemented in ODK (see above). Nutrient balance information was collected on 45 farm fields belonging to farmers included in the larger field-level individual questionnaire survey. Field areas were assessed, and partial nutrient balances were obtained as nitrogen (N), phosphorus (P), and potassium (K) in inflows (mineral fertilizer input, compost, manure, and estimated N fixation of beans as equal to harvested N) (Ojiem et al., 2007); minus export flows (harvested grain and nutrients within crop residues when these were exported). Nutrient contents of crops and manures were based on data from similar smallholder systems in the literature and unpublished data from analyses. The frequency of use of organic nutrient sources and the retention of crop residues on fields was also assessed in the survey to characterize the tendency of farmers' management to sustain soil organic carbon.

Composite soil samples were collected from the 45 farm fields in the field-level nutrient balance survey. The samples were collected to evaluate key soil properties that are known to influence plant resilience and the presence of soil-borne pathogens using a tool kit of accessible assessment methods (Nyamasoka-Magonziwa et al., 2020). These measurements included particulate organic matter (POM), permanganate-oxidizable soil carbon (POXC), aggregate stability, soil pH and phosphorus. From each field, five sub-samples were sampled to a depth of 20 cm, collected, mixed, and a sample of 1 kg was taken. Care was taken to not break aggregates during mixing for subsequent aggregate stability analysis. The soil samples were air-dried and sieved through a 2 mm sieve prior to analysis, except for the aggregate stability analysis for which a portion of the sample was carefully broken along natural planes of weakness by hand to pass a 10 mm sieve prior to drying and stability analysis (see below).

Soil pH was measured using a portable pH meter (Test Equipment Depot, Woburn, MA, USA) and particulate organic matter (POM) was determined by gentle wet-sieving of particles between 250 microns and 2 mm, followed by density flotation and decanting of organic matter in clean tap water. Permanganate oxidizable carbon (POXC; adapted from Weil et al., 2003) was measured based on the oxidation of labile soil C by potassium permanganate in a calcium chloride solution (0.015 M $KMnO_4$ and 0.1 M $CaCl_2$). Soil available phosphorus was determined using a modified Olsen method (Olsen et al., 1954) in which Olsen solution (0.5 M $NaHCO_3$, adjusted to pH 8.5 using NaOH) was used to extract reactive P which was then acidified using sodium hydrogen sulfate ($NaHSO_4$) prior to analysis for dissolved phosphate using a reagent pack for the molybdate blue colorimetric method and a low-cost colorimeter (Hanna Instruments, Providence, RI, USA). Aggregate stability was determined using wet sieving methods adapted from Nyamasoka-Magonziwa et al. (2020) and the mean weighted diameter (MWD) of three size classes (2–10, 0.25–2, and 0–0.25 mm diameters) calculated as a single parameter summarizing aggregate stability, with larger MWD representing higher stability. Soil texture was assessed by the USDA feel method (Thien, 1979; Rictchey et al., 2015).

2.4. Data analysis

Discussions with farmers in FGDs and during surveys were recorded and transcribed together with notes taken during the sessions. Transcripts were then coded and analyzed to identify recurrent themes and patterns on farmers' awareness of soil-borne insect pests and diseases, the use of pesticidal plants and other soil management issues. Data about soil nutrient and residue management were analyzed using a principal component analysis (PCA) to understand associations between site and management variables. Regression analysis was used to assess which site, soil, and nutrient management parameters were associated with farmers' perceptions of damage by soil-borne pests and diseases, subject to the insights provided by the PCA on potential confounding of soil, site, and management effects. To examine the relationship between soil factors and SPD damage, a single stunting and wilting disease index was created that was rated 1 when any symptoms of stunting and wilting were observed by farmers (e.g., wilting of seedlings, death of taproot, adventitious root formation, stunting), and 0 when none of these symptoms were observed. Multiple

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correspondence analysis assessed potential relationships between respondent demographics from the farmer surveys (age, gender and education level) and their responses on soil-borne insect pests and diseases and management practices. All analyses were carried out in XLSTAT statistical package version 2022 (Addinsoft, New York, USA).

3. Results

3.1. Participant demographics, existing knowledge, and practices

Most farmers interviewed were male (>60%) and over 80% were over 30 years old with most farmers (>50%) aged over 50 years (Table 1). Most farmers (>85%) had only completed primary education, and over 60% of respondents reported that farming was their main livelihood activity. From the sample of interviewed farmers, synthetic pesticide was reported to be a major (>72%) control method used by most farmers for whatever insect pest or disease appeared in common bean including SPDs (Figure 2). Less than half (37%) were using pesticidal plants for the management of insects in their field. On cultural management practices, >50% of farmers reported practicing intercropping of common bean and maize, >50% reported practicing timely planting, and <30% practiced crop rotation. Demographic parameters influenced some responses provided where multiple correspondence analysis showed some relationships (Figure 3). For example, the use of synthetic pesticides, intercropping and early planting correlated significantly with farmers of age >60 years whereas crop rotation correlated with farmers with age between 40 and 60 years having primary education and female farmers. Among farmers who reported using pesticidal plants, >35% used *Tephrosia vogelii*, 7% used *Tithonia diversifolia* and >3% used *Lantana camara.* All farmers reported that the parts of pesticidal plants used were leaves, which were extracted in soapy water and sprayed onto crops. These pesticidal plants were reported to work well for a variety of pests and diseases on foliar parts of plants but were not perceived as effective on SPDs.

Most farmers (60%) owned land with a majority of respondents (44%) reported farming on a land size of 0.2 ha. Farmers with larger sizes of land accounted for 40% having a land size between 0.2 and 0.4 ha. Most farmers renting land had land sizes of 0.2 ha (>55%) while almost all (90%) farmers farming on owned family farms had land sizes between 0.2 and 0.4 ha (Table 2). In the study area, fertilizer use bore no relationship to whether farmers permanently own or borrow/rent land for farming and there was no significant relationship between land size and fertilizer use.

Most farmers owned chickens (>60%) and cattle (>50%) while those who owned goats, ducks, pigs and sheep constituted a small

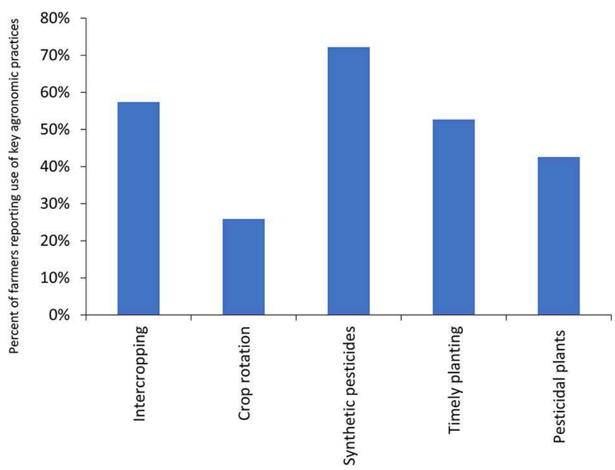

FIGURE 2
Proportion of farmers reporting use of key cultural and plant protection practices for insect pest and disease management in their fields, from a farm-level individual questionnaire in Narumu Ward, Kilimanjaro Region, Tanzania.

TABLE 1 Key demographic information about farmer respondents for 45 farmers with maize and bean fields in Narumu Ward, Kilimanjaro Region, Tanzania.

Variable	Category	All (*n* = 54)	Female	Male
			N (%)	*N* (%)
Age	<30	4	0 (0)	4(12.1)
	30–39	3	2 (9.5)	1 (3.0)
	40–49	12	5 (23.8)	7 (21.2)
	50–59	21	9 (42.9)	12 (36.4)
	≥60	14	5 (23.8)	9 (27.3)
Education level	Primary	47	21 (10)	26 (78.8)
	Secondary	4	0 (0)	4 (12.10)
	Tertiary	1	0 (0)	1 (9.1)
Livelihood activities	Farming	35	14 (66.7)	21 (63.6)
	Farming + herding	11	4 (19.1)	7 (21.2)
	Farming + small business	6	2 (9.5)	4 (11.1)

n, number of respondents; *N*(), percentage of respondents.

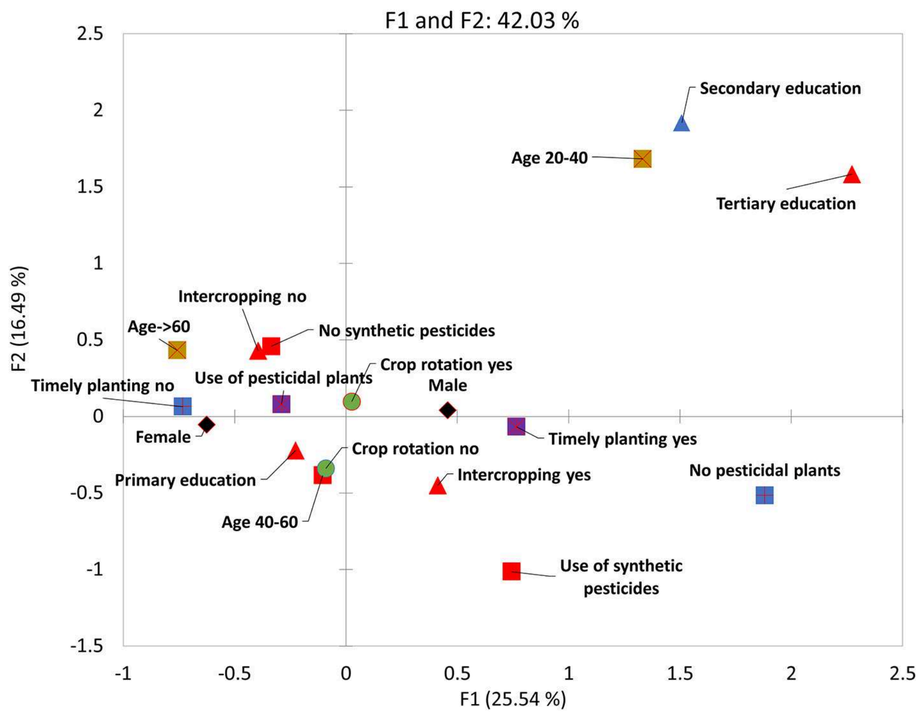

FIGURE 3
Multiple correspondence analysis showing relationships between key demographic information of respondents and their practices related to soil-borne insect pests and disease management practices, in Narumu Ward, Kilimanjaro Region, Tanzania.

TABLE 2 Land ownership and land size of respondents for 45 farmers with maize and bean fields in Narumu Ward, Kilimanjaro Region, Tanzania.

Variable	Categories	Frequencies	%
Land ownership	Does not own (e.g., rents)	18	40.0
	Owns the field	27	60.0
Crop field area (Ha)	0.1–0.19	7	15.6
	0.2	20	44.4
	>0.2	18	40.0

proportion of the respondents. More than half of farmers with cattle had a small number of cattle ranging from 1 to 6 with most farmers owning 1–4 cattle (50%) kept at their homestead surroundings. These zero-grazing practices promoted farmers to collect bean and maize residues from their fields to feed the cattle. Although it was expected that only farmers with livestock would collect crop residue for feeding their animals, all farmers with or without livestock harvested crop residues, whereas farmers with no livestock would sell the residue to farmers with livestock. Cattle manure was the only manure used for managing soil fertility in farms; however, only 3 of 45 maize and bean fields in the survey received manure, and at very low rates, suggesting that recycling of organic nutrient sources to bean and maize fields is very uncommon in these systems. Rather, all but one of the surveyed farmers reported the use of manure on homestead farms or plots near their houses ranging from small vegetable plots to large mixed plots with coffee, banana and beans (Table 3), which were often adjacent to the homestead.

Although highly variable, the manuring rates on these near plots were much higher than in the maize/bean plots, averaging 14.3 Mg ha^{-1} (standard deviation = 19.4 Mg ha^{-1}) across farms. Over 80% of manure was from farmers' own livestock with few obtaining manure from family or neighbors. Most farmers (>70%) reported that the distance to the farm was the major constraint for using manure on bean and maize fields, particularly where farmers were farming at a distance greater than five kilometers from the homestead. Another constraint reported by farmers was a lack of improved practices for composting manure as an alternative to passive methods in which the manure decomposes for 6–12 months.

3.2. Participant perceptions of soil-borne insect pests and diseases

Focus group discussions indicated that farmers in the study area were aware that insect pests damaged common bean from within the soil (Table 4). The symptoms of crop damage by soil-borne insect pests are observed mainly by uprooting the plants; however, only farmers from one group discussion reported uprooting plants to see if the damage was caused by soil-borne insects. Farmers reported root rot diseases in the field where three groups of farmers knew of such disease as soil-borne, and they reported having seen it in their farms. They perceived the diseases as soil-borne as they could observe field sections of healthy bean seedlings

TABLE 3 Distance from homes, proportion of farmers applying manure, and mean manure application rates of different crop production types of 45 farms in Narumu Ward, Kilimanjaro region, Tanzania.

Production type	Distance from homestead (km, range)	Proportion of farmers with production type (%)	Proportion of farmers with production type applying manure	Mean manure application (Mg ha^{-1}; mean ± std deviation)
Vegetable plot	< 1	18.2	100	23.6 ± 35.6
Banana-bean intercrop	< 1	4.5	100	28.2 ± 13.3
Coffee-bean intercrop	<1	59.1	3.8	0.6 ± 3.1
Coffee-banana-bean intercrop	<1	59.1	96.2	19.2 ± 26.9
Maize-bean outfields	0.5–15	100	6.7	<0.1 ± 0.1

TABLE 4 Summary of 64 farmers' responses during focus group discussions done in Narumu Ward, Kilimanjaro region, Tanzania showing perceptions about key pest insects infesting common bean plants when farmers were shown color images and dead specimens of the insect in comparison to actual scientific descriptions.

Insect pests presented to farmers ($N = 64$)	Farmer perception of the insect	Scientific description of the insect	Associated crop plant symptoms
Adult and larvae of the bean fly, *Ophiomyia phaseoli*	Thought to be larvae of the African black beetle, *Heteronychus arator*, locally named "*Nrokoo*" and thought to eat crop roots. Adults are thought to be another type of fly commonly seen in the field with no potential harm to plants.	Larvae are small and white in color whereas a fully grown larva is 2.5 mm long, yellowish white in color with black rasping hooked mouth parts, yellow-white prothoracic and posterior spiracles. Adults are shiny black with a length of 2.5 mm.	Yellowing of false leaves, stunting, wilting and death of bean plants.
Adult and larvae of the bean foliage beetle. *Ootheca bennigseni*	Larvae are not recognized. Adults are locally named "*Kirombochoo*" and are recognized as a pest damaging leaves.	The larva is elliptical, yellow and translucent. Adults are oval, 6 mm long, and shiny black with orange and dark blue streaks.	Extensive defoliation of young bean plants, wilting, premature senescence and death of plants.

without any symptoms then turning yellow a few weeks after planting. Five groups reported wilting plants, which they thought were caused by soil pests or pathogens. Participants provided with pictures of plants with *Pythium* or *Fusarium* root rot were unable to differentiate between the two pathogens. Many farmers did perceive the link between soil-borne diseases and plants turning yellow, wilting, and dying a few weeks after planting. However, participants' knowledge was limited with some remarking that root nodules on beans that provide N fixation *via* the symbiosis with *Rhizobium* bacteria were a symptom of the disease.

Field surveys showed that farmers reported bean fly and bean foliage beetle to be present in their fields for more than 3 years. Almost all farmers (90%) reported bean foliage beetle adults to be present in their fields with holes on the bean seedling leaves as the main observed symptom of insect damage. Only 6% of farmers reported seeing bean fly adults in their field but >35% of farmers reported wilting and dying of seedlings as the widely observed symptom of damage by the insect. No participant reported the presence of larvae or pupa in the soil nor attributed plant damage to them. Some farmers misdiagnosed bean fly damage, indicated by stunted plants with yellowed leaves, as anthracnose (*Colletotrichum lindemuthianum*), a fungal disease normally triggered by cold weather and high humidity. About 37% of respondents reported having root rot disease in their fields were from higher altitudes with higher humidity. All participants were aware of one key symptom of root rot, which was leaves turning yellow and dropping, followed by plants wilting and dying.

3.3. Soil fertility, soil nutrient balance and principal components analysis of site factors

Soil assessments showed that ∼70% of the fields had active carbon (POXC) in the low and very low ranges (<400 mg kg^{-1}) with the remaining group having a medium amount of POXC with the highest recorded value of <700 mg kg^{-1} (Supplementary Table 1). Almost three-quarters of the soils were either low or very low in available Olsen P (<10 mg P kg^{-1}; Supplementary Table 1) with a median value for Olsen P of 5.3 mg P kg^{-1}. Nevertheless, an analysis of soil nutrient balances on the survey fields showed that most farmers had field P balances not different from zero, regardless of whether fields were farmer-owned or not (Figure 4), due to the widespread use of synthetic fertilizers (over 95% applied fertilizer) that replaced crop exports. Meanwhile, fields owned by farmers, mostly at lower elevations, had negative N balances while those not owned had balances not different from zero on average. Negative N balances on owned fields likely relate to more frequent growing of maize in intercrops with beans on these fields, resulting in high N exports from the cereal crops, whereas on rented fields beans were more often the sole crop with lower N exports due to N fixation and the lack of a non-fixing cereal (Figure 4). On the other hand, the infrequent use of manure and the removal of residue across all the bean and maize fields, described above, is notable because it implies

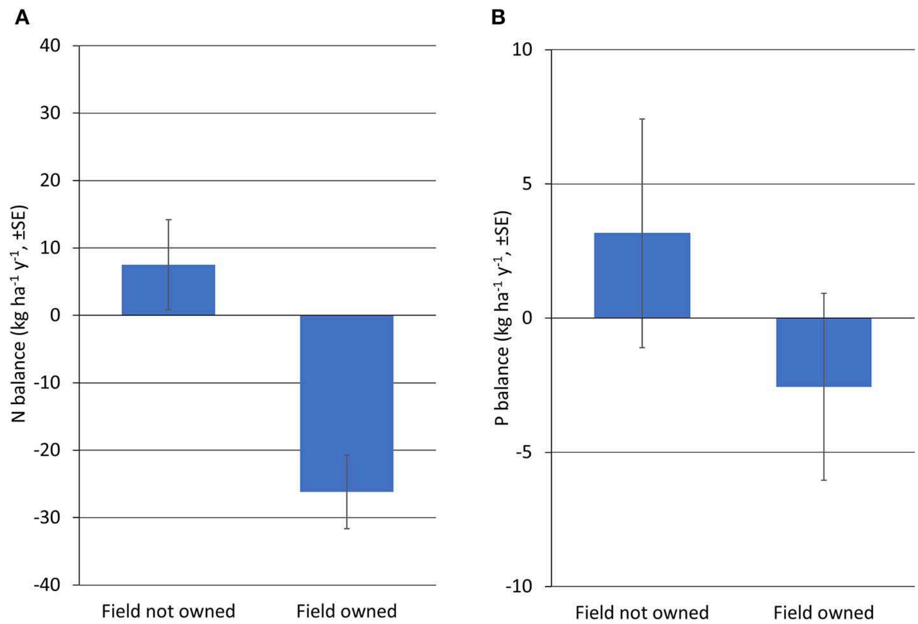

FIGURE 4
Partial nutrient balances, incorporating nutrient inputs in manure and fertilizer, estimated nitrogen fixation, and crop exports in grain and residues, based on surveys regarding 45 farmers' fields in Narumu Ward, Kilimanjaro Region, Tanzania: **(A)** nitrogen balances and **(B)** phosphorus balances, comparing fields that are owned by farmers with those not owned by farmers. Error bars show the standard error of each mean.

that little organic carbon is being returned to any of these fields (Table 3).

A principal component analysis (PCA) of site and management variables for fields (Figure 5) demonstrated a strong first component encompassing just over 30% of variability, combining pH, elevation, total inorganic N inputs, organic matter (POXC) as well as soil available P, and aggregate stability to a lesser extent. Aggregate stability (MWD of aggregates) was also positively correlated to POXC ($r = +0.55$, $p < 0.0001$, $n = 45$). Meanwhile, soil nutrient balances, total P fertilizer additions, and soil clay content were segregated into a second component (Figure 5, PC2). The third axis of variability in PC3 with 81% of the variability was loaded highly only on MWD related to aggregate stability (Supplementary Table 2). The negative association of fertilizer N inputs with elevation likely is another result of the higher frequency of maize-bean intercrops in lower fields with N fertilizer inputs during both surveyed seasons, while the association of total inorganic P inputs with P balances indicates how these inputs may be dominating the P balances across all the surveyed fields.

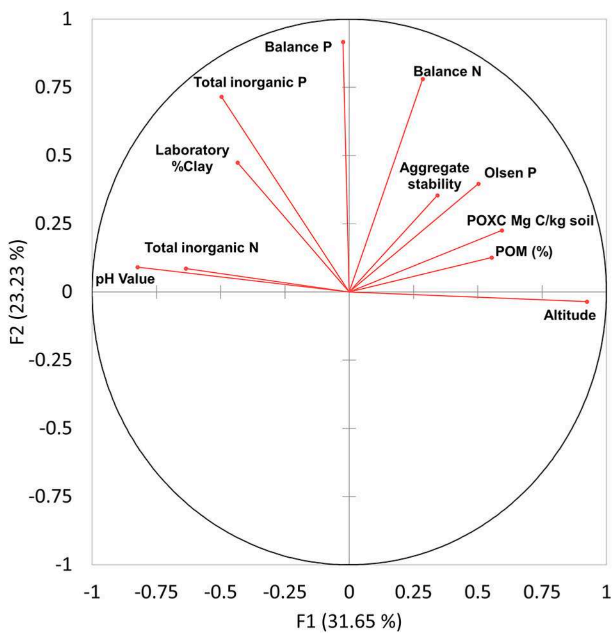

FIGURE 5
Principal component analysis of the key site and soil variables drawn from 45 farm fields for bean cultivation in Narumu Ward, Kilimanjaro Region, Tanzania. Percent variability explained by each principal component (PC) is indicated along the axes.

3.4. Linkages between site and soil factors and crop management with perceptions of soil-borne pests and disease

Logistic regressions testing the association of each of the site and management principal components, with a binary variable testing whether wilting, stunting, or root damage (S/W) was observed at each site, showed that the three principal components were all significantly associated with these farmer observations related to soil pests and diseases (Table 5). Within principal component 1 (PC1), Soil pH, soil active Carbon, and Olsen P were negatively correlated to S/W observations so that for example, fields with higher active C had lower rates of S/W reported by farmers (in

TABLE 5 Logistic regressions assessing the relationship of soil parameters and soil nutrient management predictors, with a synthetic variable summarizing observations of stunting and wilting in beans (farmers observe stunting or wilting vs. do not observe), in Narumu Ward, Kilimanjaro Region, Tanzania.

Predictor	*N*	Significance		Association with observation of stunting/wilting
Principle components				
Principle component one (PC1)	45	0.012	**	Negative
Principle component two (PC2)	45	0.035	*	Negative
Principle component three (PC3)	45	0.011	**	Negative
Individual soil parameters associated with PC 1				
Soil pH	45	0.004	**	Negative
Soil Active Carbon (POXC)	45	0.001	***	Negative
Total Inorganic N inputs in previous 2 years (kg N ha^{-1})	45	0.001	***	Positive
Soil Available P (Olsen P)	45	0.012	*	Negative
Individual soil parameters associated with PC 2				
Total Inorganic P inputs in previous 2 years (kg P ha^{-1})	45	0.403	NS	
2- year running soil P balance (kg P ha^{-1} y^{-1})	45	0.739	NS	
2- year running soil N balance (kg N ha^{-1} y^{-1})	45	0.363	NS	
Individual soil parameters associated with PC 3				
Soil aggregate stability (MWD)	45	0.003	**	Negative
Soil clay content (%)	45	0.754	NS	

Significance codes: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; NS, not significant.

fields with S/W, POXC levels of 300 ± 23 mg C kg^{-1} compared to 467 ± 41 mg C kg^{-1} in fields without S/W). By contrast, only total inorganic N inputs correlate positively with S/W, while elevation in itself was not significantly related to the S/W synthetic variable. Principal component 2 (PC2) parameters were not significantly related to S/W when tested separately (Table 5), while in PC3, fields with higher levels of aggregation (higher MWD) had lower levels of S/W.

4. Discussion

4.1. Farmers' knowledge and management of soil-borne insect pests and diseases

The surveys and focus group discussions with farmers suggested that most do not uproot seedlings or investigate roots in other ways when SPD are suspected. This is partly because farmers are not fully aware of how to assess and confirm their presence but also because it is considered a destructive method that could reduce crop yield. Farmer knowledge about bean fly and foliage beetle life cycles was largely absent with little understanding of how to observe plant damage caused by their larval stages in the soil. Damage symptoms of these pests can be similar to those arising from root rot diseases (Abate and Ampofo, 1996), where farmers made general descriptions of the yellowing of plants, stunting, wilting and death. Our results are consistent with other research that reported farmers are often confused by damage caused by bean fly and root rot disease (Buruchara et al., 2010). Holes on bean leaves were commonly reported symptoms of adult bean foliage beetle damage; however, farmers generally did not know the larval stage was a soil pest, as has been observed in other studies (Abate et al., 2000). Further confusion was evidenced by farmers who wrongly attributed bean fly larval damage to the fungal disease anthracnose (*Colletotrichum lindemuthianum*). This may indicate the inability of farmers to recognize the minute adult bean fly as a pest and then rather describe wilting and dying caused by bean fly infestation as a disease (Letourneau, 1994). Our surveys with farmers highlight that plant damage symptoms from different soil-borne pests and pathogens, such as wilting and stunting, are difficult to distinguish by farmers.

This lack of awareness about SPD has clear implications for farmers' abilities to take appropriate management actions. The first line of defense for most farmers is to use cultural practices such as early synchronous planting, using a varietal mixture of seed and intercropping (Abate and Ampofo, 1996). Such practices are considered affordable and are part of local customs, as indicated by the large number of practices in use by the oldest farmers in the MCA (Figure 3). Farmers in the area grow local bean varieties with seeds obtained from their previous harvest. The choice of varieties is based on productivity and adaptability to environmental conditions such as temperature and rainfall. This finding is consistent with research in Uganda that indicated varietal adaptability to farm conditions was one of the keys to farmer preferences for seed varieties (Bruno et al., 2018). Intercropping is commonly used in a variety of cropping systems to reduce pest incidence such as the bean foliage beetle (Farrow et al., 2011; Srinivasan, 2014). However, intercropping of beans with maize was reported to be ineffective in reducing bean fly incidence (Abate and Ampofo, 1996). Some surveys suggest that farmers do not perceive intercropping to be a pest management strategy as they report a prevalence of insect damage despite the use of the method (Laizer et al., 2019), and the observation may be quite correct in that intercropping over many adjacent farm fields supplies pests and pathogens with a constant supply of host bean plants. By contrast, crop rotation is a common cultural practice known to be effective in managing root rot and soil-borne insect pest in common bean (Mohamed and Teri, 1989). Unfortunately, in the study area, very few farmers practiced crop rotation, and among those who did, they were not doing it appropriately as 2–3 years rotation with non-host crops as recommended (Buruchara et al., 2010).

A commonly reported approach used by farmers in the study area for preventing losses from SPDs is the use of synthetic pesticides. Prior studies have noted this to be a common practice in different regions (Mwanauta et al., 2015; Stevenson et al., 2017; Andersson and Isgren, 2021). Insecticide seed treatments and foliar sprays have been recommended for bean fly and foliage beetle (Mwanauta et al., 2015), whilst fungicides and fumigants have been recommended for the control of root rots (Mahmood et al., 2017). Despite the often high cost of synthetics, many farmers use them as they fear the loss of their livelihoods and ability to feed their families. The economics of using relatively safer synthetic products is often restricted by a farmer's perceived limited capacity and autonomy to reduce pesticide use as well as what is considered "normal" practice (Bakker et al., 2021; Deguine et al., 2021). Use of synthetics is exacerbated at the smallholder level as many smallholders are unaware of alternative agro-ecological approaches (Anjarwalla et al., 2016), nor are they often aware of the hazards of synthetic use to their health (Nicolopoulou-Stamati et al., 2016; Andersson and Isgren, 2021) and the environment (Suganda et al., 2020). Farmer use of pesticidal plants has been undermined through commercial advertising and systematic promotion of synthetics over several decades by businesses and governments (Isman, 2008; Lykogianni et al., 2021). Desneux et al. (2007) advocate studying the sub-lethal effects of synthetic pesticides on natural enemies to be sure of their safe use in order to optimize IPM programs involving the use of both natural enemies and pesticides against pests. Further, Belmain et al. (2022) suggest the elimination of synthetic pesticides in order to support these natural processes and food sovereignty. Mkindi et al. (2021) recommend pesticidal plants as one alternative to synthetic pesticides. One-third of farmers in the study area reported using pesticidal plants such as *T. vogelii* and *Tithonia diversifolia*. Extracts of *T. vogelii* have been reported to have broad pesticidal properties which make them effective against most foliar and soil pests (Mkenda et al., 2014; Stevenson et al., 2017). Its use can also increase plant resilience and growth by acting as a foliar fertilizer (Mkindi et al., 2020). Other pesticidal plant species such as neem (*Azadirachta indica*) have been shown to be effective against soil-borne insects (Abate and Ampofo, 1996; Buruchara et al., 2010) where Karel and Rweyemamu (1984) reported *A. indica* to be effective in controlling bean fly in common bean.

4.2. Soil management practices and soil nutrient balance

While the cultural practices and crop protection approaches discussed above have relatively direct and short-term impacts on arthropod pests, soil fertility and organic matter management that we explored in this study are important agroecological aspects of smallholder intensification, with effects on pests and diseases at a variety of different timescales and through a complex set of mechanisms (Altieri et al., 2012; Krey et al., 2020; Belmain et al., 2022; Han et al., 2022). In this light, it is interesting that farmers observed less stunting and wilting in bean crops in fields that differed in terms of organic carbon, soil aggregation, soil available P, and recent applications of inorganic N fertilizer. These results for smallholder management contexts are consistent with more controlled experimental and observational studies suggesting for example that organic management can have positive impacts on plant defense (Krey et al., 2020), or *via* more diverse soil biological communities that can suppress pests such as pythium root rot (Larkin, 2015). It has been observed that soils with higher amounts of organic matter content have more water-stable aggregates (Gachene, 2018), and this was also the case in our study. Stable aggregates provide a habitat for a larger and more diverse microbial population which can create competitive and/or antagonistic environments between microorganisms resulting in disease suppression (Leon et al., 2006; Kevan and Shipp, 2011; Larkin, 2015). Meanwhile, the contrast between inorganic N application and soil available P in their opposite associations with stunting and wilting observations is also consistent with previous research showing that soil fertility influences the outcomes of SPDs. Soil-borne insect pests such as bean fly (*Ophiomyia* spp.) and soil-borne diseases such as root rot from *Pythium* spp. and *Fusarium* spp. are reduced in intensity when crops are grown in fertile soils and crops are less vulnerable, with phosphorus sufficiency being a key aspect (Hillocks et al., 2006; Buruchara et al., 2010; Huber et al., 2011; Samago et al., 2018). Letourneau (1994) also reported phosphorus deficiency resulted in an increase in population densities of all species of bean fly; however, increased total N increased the population of *O. spencerella*. The observation that high levels of available N predispose crops to pest damage is thought to be more generally true (Han et al., 2022).

In linking soil properties and management to stunting/wilting, our study is exploratory rather than definitive since this is an observational study that does not completely control for location, e.g., with paired plots of differing fertility and soil organic matter (SOM) status at a number of different locations. However, given the potential, and plausible links between organic matter, soil fertility, and reduced incidence of soil-borne pests and disease, the existing management of farmers raise concerns regarding sustainable intensification of bean cropping in these systems. For example, although farmers clearly used fertilizers to maintain the productivity of their maize/bean intercrops, few farmers used manure or compost in bean production fields as they lacked manure or materials for composting, and tended to use such materials in fields closer to home, often at high rates (>10 Mg ha^{-1}), which suggests the possibility of allocating some of these organic inputs to more remote maize and bean fields. The preference for enriching home fields vs. far fields in smallholder systems, and not applying fertilizer or other inputs onto beans in years where these are grown as a sole crop, has been documented in other systems (Masvaya et al., 2010; Saimon et al., 2017). In addition, although fields were in general balanced for P inputs vs. exports, available P was low across all sites and may be limiting to bean production. We note here that even though a few soil sites had strongly acidic soils which has been thought to lower the efficiency of the Olsen P extraction we used, a number of studies have shown that Olsen P performs reasonably well in acidic soils and was thus well-suited to our study which covered a wide range of soil pH from neutral to acidic (Farina and Channon, 1979; Fixen and Grove, 1990). Growing common bean with insufficient P can be detrimental to grain yield and degrade soil fertility (Araújo et al., 2000; Samago et al., 2018; Meya et al., 2020) as P contributes to effective N fixation (Hernández et al., 2009) and resistance to SPDs as discussed above (Huber et al., 2011). One important observation from our study is that regardless of whether farmers owned or did not own fields, they prioritized soil health and fertility improvement less than they did crop productivity. Other studies have argued that neglecting soils is especially prevalent for farmers who do not have long-term farm tenure and are less committed to investment in soil improvement (Williams, 1999). Conversely, land ownership can potentially lead to management practices that increase SOM affecting soil health (Mganga et al., 2016). However, in our study, few farmers were using manure irrespective of owning the field or not, likely due to transport costs, lack of skills in manure processing and composting, and relatively few cattle in the area. They were however applying more fertilizer to owned plots in order to plant maize every season, even if the balances in these plots were negative on average, due to high levels of N export by maize.

Crop residue removal can also contribute to the loss of SOM (Mganga et al., 2016) which could have beneficial effects on the management of some pests and diseases (Leon et al., 2006; Janvier et al., 2007). Farmers in the area generally use crop residue as livestock feed, and according to our survey, even farmers without livestock sold residue to those with animals. Beyond distance to fields and knowledge of manure management, our results likely do not capture all the factors that determine farmers' use of manure and crop residues, such as labor constraints and the monetary gain from selling residues; part of increasing the recycling of organic materials to soils would be to better understand and address these factors with evidence regarding soil health benefits of recycling residues (Adimassu et al., 2016; Mponela et al., 2016). Crop harvests, residue removal and lack of any organic inputs through animal manure or green mulches suggest that soil structure and organic matter content have likely been degraded in the majority of farmer fields in the area over decades of using such farming practices (Rurangwa et al., 2018), resulting in the low levels of active C observed in this study in many fields. Reversing these trends will likely require investment in better understanding residue use decisions and raising awareness of farmers and training that aims at restoring soil health such as maintaining agricultural residues, application of organic fertilizers, crop rotation, nutrient and carbon recycling (Bunning and Jiménez, 2003; Martinez-Salgado et al., 2010). Though challenging for many farmers, these practices can augment the soil's organic carbon pool, a key indicator of soil quality linked to soil aggregation, available water holding capacity and reduced erodibility of soil (Lal, 2006). Increased SOM will support an increased abundance of microorganisms that are necessary to sustain many soil functions such as the decomposition of organic matter (Janvier et al., 2007), maintenance of soil structure (Puget et al., 2000) and suppression of above and below-ground pests, parasites and diseases (Leon et al., 2006; Janvier et al., 2007; Altieri et al., 2012).

5. Conclusions

A main conclusion from this study with relevance to other African smallholder communities undergoing the intensification of farming is that farmers' awareness of SPDs in the study area is low, which has directly facilitated the prevalence of these biotic production constraints. Therefore, knowledge of these pests and diseases, including their relation to soil factors, should be promoted to motivate changes toward agroecological management of soil pests and pathogens. Further research also needs to explore specific soil mechanisms that are relevant or achievable in smallholder contexts, that may deter or encourage particular pests and pathogens, which are not sufficiently explored in this characterization study. In addition, learning approaches for farmers should be tailored to their needs by considering farmers' current practices, including cultural and soil management, and also aligning with the FAO's elements of agroecological farming for pest and disease management (Belmain et al., 2022) This could involve increased use of pesticidal plants, particularly species such as *T. vogelii* that have been shown to control a wide variety of pests, increase crop plant resilience and help to improve the soil where it is growing due to its deep roots and nitrogen-fixing properties (Belmain et al., 2022). Use of manure, compost, green mulching, short fallows, and other organic inputs need to be facilitated through dialogue with farmers to develop socially and economically sustainable practices alongside them, whilst also improving soils to maintain productivity and also reduce chronic soil-borne pest and disease problems.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Tanzania Commission for Science and Technology (2021-181-NA-2021-061). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

ZN, AM, PS, SB, SV, and PN contributed to the conceptualization of the study. ZN, AM, PS, SV, and SB structured the methodology. ZN, AM, and SV wrote the first draft of the manuscript. SV and AM cleaned and managed data. ZN, AM, SV, and SB performed the statistical analysis. AM, SV, PN, and SB mobilized resources for publication.

AM, SV, PN, PS, and SB reviewed and edited the manuscript. All authors have contributed to manuscript revision, read, and agreed to the published version of 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1094739/full#supplementary-material

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EDITED BY
Terry Ansah,
University for Development Studies, Ghana

REVIEWED BY
Solomon Konlan,
Council for Scientific and Industrial Research (CSIR), Ghana
Adugna Tolera,
Hawassa University, Ethiopia
Bambang Suwignyo,
Gadjah Mada University, Indonesia

*CORRESPONDENCE
Prince Sasu
✉ psasu.research@gmail.com

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Comparative nutritional evaluation of the leaves of selected plants from the Poaceae family (bamboos and grasses) for sustainable livestock production in Ghana

Prince Sasu[1]*, Victoria Attoh-Kotoku[1], Antoinette S. Anim-Jnr[1], Alhassan Osman[1], Obed Adjei[1], Benjamin Adjei-Mensah[2], Dora Edinam Aku Akoli[1], Rachida Adjima Tankouano[2], Michael Kwaku[3] and Daniel Obloni Kweitsu[3]

[1]Department of Animal Science, Faculty of Agriculture, College of Agriculture and Natural Resources, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana, [2]Centre d'Excellence Régional en Sciences Aviaires (CERSA), Université de Lomé, Lome, Togo, [3]International Network for Bamboo and Rattan (INBAR), Kumasi, Ghana

Background: Sustainable animal feeding is essential for reducing poverty among Ghanaian smallholder livestock farmers. However, seasonality has a severe impact on the availability and quality of conventional animal feedstuffs, necessitating alternate feed sources.

Objective: This study evaluated and compared the nutritional characteristics of the leaves of three bamboo species namely; *Bambusa balcooa (Beema), Oxytenanthera abyssinica (A. Rich.) Munro and Bambusa vulgaris;* and three conventional types of grass, namely; *Cenchrus purpureus, Megathyrsus maximus, and Brachiaria decumbens*.

Materials and methods: The plant biomasses were subjected to the standard analytical procedures of proximate and detergent fiber systems to highlight their dry matter (DM), crude protein (CP), crude fiber (CF), ether extract (EE), ash, nitrogen-free extract (NFE), neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL). Other nutritional characteristics were estimated using the chemical compositions.

Statistical analysis: Data was analyzed using Generalized Linear Model procedures in Minitab Statistical Software at a 5% significant level.

Results: Results showed a significantly ($P < 0.05$) higher DM (∼918 g/kgDM), CP (∼153 g/kgDM), and EE (∼153 g/kgDM) in *B. vulgaris leaves*. *O. abyssinica* leaves had the maximum ash (∼139 g/kgDM) while those of *M. maximus* had the highest carbohydrate (∼709 g/kgDM) and CF (∼492 g/kgDM). Compared to the grasses, the bamboo had a higher pool of DM (∼910 vs. 836 g/kgDM), CP (∼133 vs. 75 g/kgDM), EE (∼137 vs. 82 g/kgDM), ash (∼134 vs. 89 g/kgDM), hemicellulose (∼79 vs. 28 g/kgDM), dry matter intake (∼25 vs. 24%), digestible dry matter (∼58 vs. 53%), and relative feed value (∼111 vs. 105). In contrast, the grasses had higher mean ADF (∼461 vs. 402 g/kgDM), cellulose (∼417 vs. 397 g/kgDM), and ADL (∼5 vs. 0.4 g/kgDM).

Conclusion: The study suggests that bamboo leaves could have high nutritional characteristics to supplement or even replace conventional grasses and other crop residues in the diets of ruminants, especially during the dry season.

KEYWORDS

bamboo leaves, sustainable feed production, smallhold farming systems, livestock, Ghana

Introduction

The demand to intensify livestock output grows as the majority of people in Sub-Saharan Africa (SSA) consume mainly meat and meat products to meet their daily protein requirements. However, livestock intensification puts pressure on the amount of feed that farmers can access, especially in urban and peri-urban areas of SSA (Graefe et al., 2008). A decrease in feed supply as a result of the conversion of grazing lands into arable lands and infrastructure development exacerbates the poor livestock output, particularly during the dry season since most livestock farmers rely mainly on native pastures (Smith, 2010; Awuma, 2012; Ansah and Issaka, 2018).

According to estimates [Statistical Research and Information Directorate (SRID), 2014], Ghana's native vegetation (pastures without improvements) covers about 26,000 km^2 (11% of the country's total land area), and if the additional 63,000 km^2 (or 26% of the total land area) of uncontrolled savannah woodland area is included, the amount of potentially usable land for grazing is estimated to be 89,000 km^2 (or 37% of the total land area). Additional forage may be provided by portions of fallowed lands [Statistical Research and Information Directorate (SRID), 2014]. It is estimated that 10,600,000 tons of fodder are produced nationwide, with around 70% coming from grassland (Ziblim et al., 2015). The widespread grasses and forbs that makeup Ghana's grassland are frequently consumed and preferred by livestock including but not limited to *Tridax procumbens, Tephrosia purpurea, Sida acuta, Pennisetum pedicellatum, Andropogon pseudapricus, Amarantus spinosus, Commelina sp, Boerhavia diffusa, Cenchrus purpureus, Paspalum scrobiculatum, Isoberlinia tomentosa, Vetiveria nigritana, Megathyrsus maximus, Cymbopogon giganteus, Andropogon gayanus, Imperata cylindrica, Sporobulus pyramidalis, Ellinsia guinensis, Combretum mole, Zornia glochidiata, Setaria pallide-fusca, Rottboellia cochinchinensis, Allysicarpus ovalifolius, Indigofera sp, Cyperus rotundus* and *Stylosanthes mucronate* (Ziblim et al., 2015). These fodder resources make up a significant portion of the feed for livestock, particularly ruminants. However, their availability to animals varies throughout the year. Additionally, even though, some resistant and nutrient-dense leguminous forages are over-sown on grazing grounds for communal use, this technique is uncommon and is only permitted at state livestock stations where grazing land is set aside (Oppong-Anane, 2006). In a similar array, the use of crop residues in crop-livestock systems has been expanding to augment natural pastures (Samdup et al., 2010). In these supposedly less cumbersome systems, goats and sheep are either allowed to forage on crop wastes or are tethered. However, these tethered animals typically produce less since they have less access to forages. Even worse, to guarantee access to enough pasture, it is necessary to move the animals to new areas each day, increasing labor costs.

Aside limited supply of feed and fodder throughout the entire nation, the country's typical rainfall pattern has an impact on the growth patterns of these forages in different ecological zones. Even in areas where the dry matter supply is sufficient throughout the dry season, it is severely deficient in protein, vitamins, and minerals (Oppong-Anane, 2006). At the start of the rainy season, the dry matter is estimated to typically contain crude protein between 8 and 12%, and as low as 2–4% in the dry season, while phosphorus concentration ranges from 0.16–0.06% DM (Agrovets Consultancy, 1989). There is, therefore, a need to investigate additional non-conventional and/or underutilized feed and fodder options to supplement the current ones and eventually replace the scarce ones.

One promising alternative is bamboo leaves. Bamboo, which is primarily evergreen (INBAR, 2019; Sasu et al., 2023), belongs to the grass (Poaceae) family (Armstrong, 2008), and is described as an "unfamiliar" plant (INBAR, 2019), yet a "wonder" plant (Zehui, 2007). The bamboo plant is noted for producing a large amount of leaf biomass and can be used as a viable source of both green and dry roughages for smallholder livestock farming communities (Sasu et al., 2023). Ghana has an estimated 42,889.63 hectares of indigenous bamboo stands, predominantly distributed in the southern regions of the country as natural stands (INBAR, 2020a,b). The Ashanti region has the largest bamboo area (10,325.51 ha), followed by the Central (9,518.23 ha), Western (9,397.49 ha), Eastern (8,991.80 ha), and Western North regions (4,656.60 ha). The distribution of bamboo in Ghana is ecologically linked to moist ecozones, mainly moist semi-deciduous and moist evergreen, with less bamboo present in dry ecozones such as dry semi-deciduous and savannah. Literature on Ghana bamboo (INBAR, 2020b) shows that some exotic species, such as the thick-walled Beema (*Bambusa balcooa*) bamboo from India and the near-solid *Oxytenanthera abyssinica* from Ethiopia, have been introduced into Ghana. These species are well adapted to drier areas and are particularly useful for biomass energy. Bamboo harvesting and use for furniture production and construction scaffolding are common in Ghana (INBAR, 2020b), while the leaves are often left unattended to. Nonetheless, it is established that various wild animals, including pandas and goats, commonly graze on new bamboo shoots and leaves from the lower sections of bamboo stems as a source of wild forage (Hayashi et al., 2005; Asaolu et al., 2009; Halvorson et al., 2011). Bamboo leaves are particularly promising as a feed source for ruminant livestock during the dry season in Ghana, as they can withstand drought conditions better than most pasture grasses. In fact, bamboo leaves have been referred to as the "hope" for dry season ruminant livestock production in Ghana (Sasu et al., 2022). Mammalian herbivores, including ruminant animals, commonly exhibit dietary diversity (Distel et al., 2020). Ruminant animals have the ability to choose from various types of food with different nutrient concentrations, allowing them to select diets that meet their nutritional needs while avoiding toxicity and nutritional disorders (Villalba et al., 2002, 2004). Bamboo, therefore, has the potential to be a suitable fodder plant as its leaves can provide a perfect feed resource that aligns with the selective nature of ruminant animals. Furthermore, foraging hens eat the newly sprouted shoots, while goats graze the lower leaf sections that are not overgrown (personal observation). This demonstrate that bamboo is a natural feed source for animals and may present grazing livestock species with an acceptable feed alternative and supplement to their daily nutritional requirements.

Despite these promising attributes of bamboo plants and their consistent supply of edible leaves especially during the dry season as noted by Antwi-Boasiako et al. (2011), INBAR (2019), Sasu et al. (2022, 2023), the use of bamboo leaves as animal feed is still in its infancy in most parts of Africa, and specifically, it has not gained much popularity in Ghana. There is, therefore, a need for more research to be conducted on the feasibility of using them as a source of animal feed in different ecological zones in the region.

It is against this background that the current study sought to explore the nutritional quality and fodder potentials of the leaves of three bamboo species, namely; *Oxytenanthera abyssinica (A. Rich.) Munro, Bambusa balcooa (Beema),* and *Bambusa vulgaris* through analytical comparison with three selected conventional types of grass, namely; *Cenchrus purpureus, Megathyrsus maximus,* and *Brachiaria decumbens*. This research could help to unlock the potential of bamboo fodder as a sustainable and cost-effective source of animal feed, which could help to support the growth of the livestock sector in Sub-Saharan Africa and improve food security in the region. The findings of this study may particularly be helpful to smallholder farmers who primarily rely on natural pasture and agricultural wastes as their main sources of animal feed.

Materials and methods

Study area

The study took place at the Livestock Section of the Department of Animal Science, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi during the dry season from late November 2020 to mid-February 2021. The area is in the semi-deciduous humid forest zone of Ghana which experiences a bimodal rainfall pattern of 1,300 mm per year. The average daily temperature is 26°C, with daily temperatures ranging from 20 to 35°C. During the wet season, relative humidity ranges from 97% in the morning to as low as 20% in the late afternoon with daily temperatures ranging from 20 to 35°C and relative humidity of 67–80% (Unpublished 2021 meteorological data, Department of Animal Science, KNUST).

Source of plant leaf biomass, sampling procedure, and sample preparation

The study involved collecting plant samples from different locations for further analysis. Fresh leaves of ∼3½ years old *Oxytenanthera abyssinica (A. Rich.) Munro* and *Bambusa balcooa (Beema)* bamboo species were collected from the INBAR[1] bamboo agroforestry site, while the leaves of another bamboo *(Bambusa vulgaris)* with similar age were sampled from their mature stands that naturally grow in the KNUST Botanical Garden, near the study site. For the grasses, fresh leaves from the regrowth of *Cenchrus purpureus, Megathyrsus maximus,* and *Brachiaria decumbens* were sampled on their natural growing fields within a 1-kilometer radius of the Department of Animal Science, KNUST, where the study was conducted. The sampling of the leaves from all the plant species was done in three separate locations on the field, and distinct plant branches were considered provided they were not conspicuously over-matured. For each plant biomass, ∼3.0 kg of representative samples were harvested, packed in air-tight bags separately, and transported to the laboratory for further analysis.

At the laboratory, triplicate samples of each plant biomass were prepared based on the three sampling locations to get statistical repetitions. The samples were chopped into smaller pieces and allowed to air dry in a room for 24 h. Afterwards, they were dried in an oven at 60°C for 48 h until a constant weight was achieved. The oven-dried samples were then coarsely milled using a laboratory mill (Wiley Mill)[2] to pass through a 2 mm screen before being placed in Ziploc bags for chemical and nutritional analyses.

Laboratory chemical analyses

The proximate analytical procedure was employed, following the standard procedures of the Association of Official Analytical Chemists (AOAC, 1990) to determine the nutritional composition of the collected plant biomass samples. The procedure included the determination of dry matter (DM), crude protein, ether extract (EE), crude fiber (CF), and ash. Dry matter (DM) was determined by drying the samples in a hot air oven at 105°C for 8 h, while total ash was analyzed by incineration at 550°C for 8 h in a muffle furnace. Crude protein (was calculated from the nitrogen values (CP = N concentration * 6.25) using the Kjeldahl method (Rothman et al., 2006). All amino acids contain N, in the amino group, and plant and muscle proteins contain on average 16% N, so multiplying the N concentrations by 6.25 (i.e., 100% divided by 16%) gives a value for the protein content of the experimental plant biomasses. To determine the crude fiber content, the samples were subjected to acid and base digestion before incineration.

1 International Network of Bamboo and Rattan (INBAR) bamboo agroforestry cultivated in the Sekyere Central District of Ashanti Region, Ghana.

2 The Thomas ® Model 4 Wiley Mill. Made in the USA. Marketed and distributed by Onrion LLC. 93 South Railroad Avenue, STE C Bergenfield, 07621-2352, New Jersey, USA.

The nitrogen-free extract (NFE) and carbohydrate (CARB) were estimated using the formulae described by Agolisi et al. (2020).

$$NFE, \% = 100 - (\% \, moisture + \% \, fat + \% \, crude \, fibre\% + \% \, Protein + \% \, ash) \quad (1)$$

$$CARB, \% = 100 - (\% \, moisture + \% \, fat + \% \, Protein + \% \, ash) \quad (2)$$

To determine the contents of neutral detergent fiber (NDF) and acid detergent fiber (ADF), the ANKOM[3] 2000 Automated Fiber Analyzer was used, and standard procedures as described by Van Soest et al. (1991) were followed. Acid detergent lignin (ADL) was evaluated by subjecting the acid detergent fiber residue to 72% sulphuric acid. All analyses were carried out in triplicate for each sample of the collected plant biomass.

The non-structural carbohydrate (NSC) was determined according to the formula by Van Soest et al. (1991);

$$NSC, \% = 100 - (\%NDF + \%CP + \%EE + \%ASH) \quad (3)$$

The hemicellulose (HEM) and cellulose (CEL) contents were estimated as proposed by Hindrichsen et al. (2006) as follows:

$$HEM, \% = \%NDF - \%ADF \quad (4)$$

$$CEL, \% = \%ADF - \%ADL \quad (5)$$

Feed quality estimation

The feed quality was determined by estimating the dry matter intake (DMI), digestible dry matter (DDM), and relative feed value (RFV) using the following equations (Rohweder et al., 1978).

$$DMI, \% \, of \, body \, weight = \frac{120}{NDF \, (\% \, of \, DM)} \quad (6)$$

$$DDM, \% \, of \, DM = 88.9 - [ADF \, (\% \, of \, DM)] * 0.779) \quad (7)$$

$$RFV = \frac{DMI * DDM}{1.29} \quad (8)$$

Statistical analysis

All data were analyzed using the GLM procedure of Minitab Statistical Software, version 19.0 (Minitab, LLC, NY, US, 2019). The chemical compositions (DM, CP, CF, EE, NFE, ash, NDF, ADF, ADL, NSC, CEL, and HEM, DDM, DMI, and RFV) were considered as the response (variables) whilst the plant species evaluated were considered as the factors (fixed term) using the three different sampling locations as statistical replications. As discussed by Hogg and Ledolter (2011), assumptions that underpinned the ANOVA procedure were: (1) The values for nutrient levels follow a normal distribution, and (2) The variances are the same for each nutrient level. The following model was used: $Y_{ij} = \mu + N_i + e_{ij}$, where $Y_{ij=}$ observed variation, μ = population means, N_i = nutritional values in the test forages and e_{ij} = error term. Significant differences among sample means were tested using Turkey's pairwise comparison at 5% ($P < 0.05$).

3 The ANKOM 2000 Automated Fiber Analyzer. Made in USA. Marketed and distributed by ANKOM Technology, Macedon NY 14502, 2052 O'Neil Road.

Results

Analytical chemical compositions of bamboo and grass leaf samples

The results showed significant heterogeneity ($P < 0.05$) in dry matter (DM), crude protein (CP), crude fiber (CF), nitrogen-free extract (NFE), carbohydrate (CARB), ether extract (EE), and ash among the leaves assayed (Table 1). Results showed that *B. vulgaris* had the highest dry matter (DM) content (917.7 g/kgDM), while *C. purpureus* had the lowest value (790.7 g/kgDM). The highest crude protein (CP) value was reported for *B. vulgaris* (152.9 g/kgDM) and *M. maximus* had the lowest value (53.7 g/kgDM). In terms of ash content, *O. abyssinica* had the maximum value (138.8 g/kgDM), while *C. purpureus* had the minimum value (64.3 g/kgDM). *B. vulgaris* had the highest ether extract (EE) value (152.6 g/kgDM), while *M. maximus* had the lowest value (43.7 g/kgDM). *B. balcooa* had the highest nitrogen-free extract (NFE) value (246.4 g/kgDM), while *C. purpureus* had the lowest value (127.2 g/kgDM). The lowest crude fiber (CF) value was found in *B. decumbens* (285.8 g/kgDM), and the highest value was in *M. maximus* (492.4 g/kgDM). *M. maximus* had the maximum carbohydrate (CARB) content (708.5 g/kgDM), while *B. vulgaris* had the lowest value (481.7 g/kgDM).

When the nutrient compositions were pooled and compared (Figure 1), the mean values suggest that bamboo leaves were more nutrient-dense ($P < 0.05$), with mean DM (910.3 g/kgDM), CP (133.0 g/kgDM), ash (133.6 g/kgDM), and EE (137.3 g/kgDM), but lower mean CF (321.3 g/kgDM) and CARB (506.4 g/kgDM) than the grasses, which had a mean DM of 835.5 g/kgDM, CP of 75.1 g/kgDM, ash of 88.7 g/kgDM, EE of 82.0 g/kg/DM, CF of 407.4 g/kgDM, and CARB of 589.7 g/kgDM.

Detergent fiber fractions of bamboo and grass leaf samples

As summarized in Table 2, the fiber fractions of the leaves significantly varied ($P < 0.05$) in the amount of neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), non-structural carbohydrate (NSC), cellulose (CEL), and hemicellulose (HEM) with the highest NDF and ADF content (509.5 and 484.7 g/kgDM respectively), were found in the leaves of *C. purpureus* while the lowest content (468.8 and 386.1 g/kgDM respectively) were recorded in the leaves of *O. abyssinica*. The maximum HEM concentration was observed in the leaves of *B. vulgaris* (87.9 g/kgDM) and the minimum concentration was found in those of *B. decumbens* (12.1 g/kgDM). The leaves of *B. decumbens* had the lowest NSC content (365.0 g/kgDM), while *M. maximus* had the highest ($P < 0.05$) NSC content (432.7 g/kgDM). A higher ($P < 0.05$) level of CEL was recorded for *M. maximus* (440 g/kgDM), whereas *B. decumbens* leaves had the lowest ($P < 0.05$)

TABLE 1 Analytical proximate compositions of bamboo leaves and grass samples.

Plant leaf biomass	Composition (g/kgDM)						
	DM	CP	CF	NFE	CARB	EE	ASH
[a]Grasses							
C. purpureus	790.7[c]	80.0[c]	444.0[b]	12.7[c]	571.2[b]	75.3[d]	64.3[c]
M. maximus	894.7[b]	53.7[d]	492.4[a]	21.6[ab]	708.5[a]	43.7[e]	88.8[bc]
B. decumbens	821.0[b]	91.5[bc]	285.8[d]	20.3[b]	489.3[c]	127.1[bc]	113.1[ab]
[b]Bamboo leaves							
O. abyssinica	904.3[a]	142.9[a]	333.0[c]	14.7[c]	479.7[c]	142.9[ab]	138.8[a]
B. balcooa	909.0[a]	103.1[b]	311.4[c]	24.6[a]	557.8[b]	116.4[c]	131.6[a]
B. vulgaris	917.7[a]	152.9[a]	319.4[c]	16.2[c]	481.7[c]	152.6[a]	130.3[a]
SEM	0.816	0.336	0.470	0.699	0.724	0.396	0.509
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means of each parameter along a column with different superscripts (a, b, c, d, e) differed significantly ($P < 0.05$). SEM, standard error of means.
DM, dry matter; CP, crude protein; CF, crude fiber; NFE, nitrogen-free extract; CARB, carbohydrate; EE, ether extract.
[a]Grasses, Cenchrus purpureus, Megathyrsus maximus, and Brachiaria decumbens.
[b]Bamboos, Bambusa balcooa (Beema), Oxytenanthera abyssinica (A. Rich.) Munro and *Bambusa vulgaris*.

CEL (383.2 g/kgDM). The level of ADL was highest ($P < 0.05$) in *B. decumbens* leaves (7.5 g/kgDM) and lowest ($P < 0.05$) in *O. abyssinica leaves* (0.2 g/kgDM).

Comparatively (Figure 2), the mean pools of neutral detergent fiber (NDF) and non-structural carbohydrate (NSC) were similar ($P > 0.05$) between bamboo and grasses. However, the grasses had relatively higher fiber fractions than bamboo leaves ($P < 0.05$), with mean levels of acid detergent fiber (ADF) at 461.4 g/kg DM compared to 402.7 g/kg DM for bamboo leaves, and cellulose (CEL) at 417.0 g/kg DM compared to 397.4 g/kg DM for bamboo leaves. Grasses also had lower content of hemicellulose (HEM) at 27.9 g/kgDM compared to 79.3 g/kgDM for bamboo leaves.

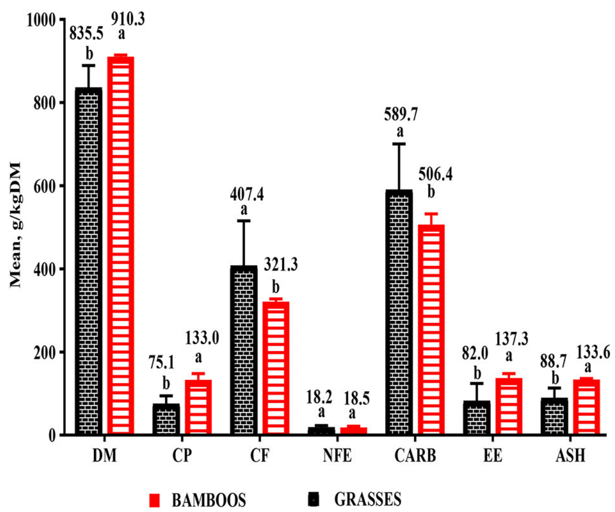

FIGURE 1
Average proximate and fiber pools for bamboo (*Bambusa balcooa (Beema), Oxytenanthera abyssinica (A. Rich.) Munro* and *Bambusa vulgaris)* and grass (*Cenchrus purpureus, Megathyrsus maximus, and Brachiaria decumbens*) leaf biomasses. Data points are mean of means ($n = 3$) ± SEM. Data bars *with similar superscripts (a, b)* are not *significantly different ($p > 0.05$);* DM, dry matter; CP, crude protein; CF, crude fiber; EE, ether extract: NFE, nitrogen-free extract; CARB, carbohydrate.

Feed quality indices and grading of bamboo and grass leaf samples

Table 3 provides estimates of dry matter intake (DMI), digestible dry matter (DDM), relative feed value (RFV), and the quality scale for grading bamboo leaves and grasses. The estimates of DMI were similar ($P > 0.05$) in the leaves of *O. abyssinica* and *B. decumbens* (25.1 vs. 24.9% BW), which were slightly higher ($P < 0.05$) than the values obtained for *B. balcooa* and *B. vulgaris* (both 24.8% BW), and those obtained for *C. purpureus* and *M. maximus* (both 24.1% BW).

The DDM estimates ranged from the highest ($P < 0.05$) in the leaves of *O. abyssinica* (58.8%), which was similar ($P > 0.05$) to those of *B. vulgaris*, followed closely ($P < 0.05$) by 55.9% in both *B. balcooa* and *M. maximus*, and 53.2% in *B. decumbens*, while the least estimate of 51.1% was obtained for *C. purpureus*.

Regarding the relative feed value, the leaves of *O. abyssinica* bamboo had the highest ($P < 0.05$) feeding value among the plants tested and were nutritionally comparable ($P > 0.05$) to *B. decumbens* grass (both with an RFV of 116.7), followed ($P < 0.05$) by both *B. vulgaris* (110.3) and *B. balcooa* (106.3), which were followed closely ($P < 0.05$) by *M. maximus* (103.8). However, *C. purpureus* had the lowest ($P < 0.05$) value (93.4).

Except for *C. purpureus*, which was considered of fair quality with a score of "3" on the grading scale, all the plant biomasses were given a score of "2," indicating good quality forage.

TABLE 2 Analytical detergent fiber fractions of bamboo and grass leaf samples.

Plant leaf biomass	Composition (g/kgDM)					
	NDF	ADF	ADL	NSC	HEM	CEL
^{a}Grasses						
C. purpureus	509.5^a	484.7^a	5.7^b	430.9^a	24.8^d	427.9^a
M. maximus	488.5^b	441.6^{bc}	1.7^c	432.7^a	46.9^{bc}	440.0^a
B. decumbens	470.1^c	458.0^b	7.5^a	381.2^b	12.1^d	383.2^b
^{b}Bamboo leaves						
O. abyssinica	468.8^c	386.1^d	0.2^d	392.3^b	82.7^a	384.4^b
B. balcooa	490.0^b	422.6^c	0.5^d	365.0^b	67.4^{ab}	422.1^a
B. vulgaris	488.5^b	399.3^d	0.4^d	382.7^b	87.9^a	385.6^b
SEM	0.313	0.424	0.019	0.925	0.453	0.349
P-value	<0.001	<0.001	<0.001	0.002	<0.001	<0.001

Means of each parameter along a column with different superscripts (a, b, c, d) differed significantly ($P < 0.05$). DM, dry matter. SEM, standard error of means.
NDF, neutral detergent fiber; ADF, acid detergent fiber; ADL, acid detergent lignin; NSC, non-structural carbohydrate; HEM, hemicellulose; CEL, cellulose.
[a]Grasses, Cenchrus purpureus, Megathyrsus maximus, and Brachiaria decumbens.
[b]Bamboos, Bambusa balcooa (Beema), Oxytenanthera abyssinica (A. Rich.) Munro and *Bambusa vulgaris*.

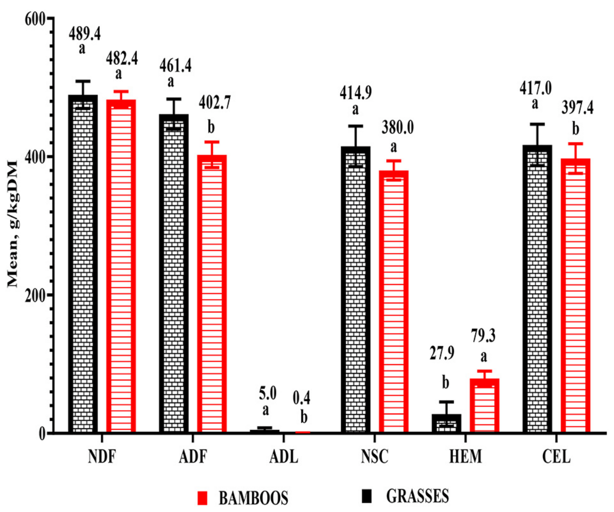

FIGURE 2
Average detergent fiber pools for the leaf biomasses of bamboo (*Bambusa balcooa (Beema), Oxytenanthera abyssinica (A. Rich.)* Munro and *Bambusa vulgaris)* and grass (*Cenchrus purpureus, Megathyrsus maximus,* and *Brachiaria decumbens*). Data points are mean of means ($n = 3$) ± SEM. Data bars *with similar superscripts (a, b)* are not *significantly different (p > 0.05);* NDF, neutral detergent fiber; ADF, acid detergent fiber; ADL, acid detergent lignin; NSC, non-structural carbohydrate; HEM, hemicellulose; CEL, cellulose.

TABLE 3 Estimated forage quality indices for bamboo and grass leaf samples.

Plant leaf biomass	DMI,% BW	DDM,%	RFV	*Forage quality grading
^{a}*Grasses*				
C. purpureus	24.1^c	51.1^d	93.4^d	3 (fair)
M. maximus	24.1^c	54.5^{bc}	103.8^c	2 (good)
B. decumbens	24.9^a	53.2^c	116.7^a	2 (good)
Mean	*(24.4)	* (52.9)	* (104.6)	
^{b}Bamboos				
O. abyssinica	25.1^a	58.8^a	116.7^a	2 (good)
B. balcooa	24.8^b	55.9^b	106.3^{bc}	2 (good)
B. vulgaris	24.8^b	57.7^a	110.3^b	2 (good)
**Mean*	*(24.9)	* (57.5)	*(111.1)	
SEM	0.137	0.642	1.029	
P-value	0.123	<0.001	<0.001	

Within the column, parameters with similar superscripts (a, b, c, d) are not significantly different ($p > 0.05$). *Values in parenthesis, column mean estimates for grasses and bamboo; SEM, standard error of means; DMI, dry matter intake; DMD, digestible dry matter; RFV, relative feed value.
*Quality Grading Standard assigned by The Hay Marketing Task Force of the American Forage and Grassland Council, the RFV was assessed as roughages based on prime >151; 1 (premium) = 151–125; 2 (good) = 124–103; 3 (fair) = 102–87; 4 (poor) = 86–75; 5(reject) < 75 (Rohweder et al., 1978).
[a]Grasses, Cenchrus purpureus, Megathyrsus maximus, and Brachiaria decumbens.
[b]Bamboos, Bambusa balcooa (Beema), Oxytenanthera abyssinica (A. Rich.) Munro and *Bambusa vulgaris*.

Discussion

The nutritional composition of forages plays a critical role in ruminant nutrition, and different analytical methods are used to determine forage nutrient content. Proximate analysis, detergent fiber analysis, and relative feed quality analysis are commonly used methods for assessing the nutritional quality of forages. These analytical methods are important in evaluating the nutritional value of grasses and bamboo leaves for ruminant nutrition and can help guide dietary choices for optimal animal health and production. In this context, the results obtained from these analyses are discussed in more detail in order to highlight their importance in ruminant nutrition.

In this study, there were significant nutritional disparities between the grasses and bamboo leaves which could be linked to their different genetic makeup and the prevailing edaphic conditions during the dry season when this study was conducted. The bamboo leaves had a higher dry matter content compared to the grasses, suggesting that they are relatively more nutrient-dense. However, it is worth noting that the dry matter content of bamboo leaves was higher than what is typically found in most fresh forages. This difference could be due to the prevailing dry condition during the study period, which likely reduced the moisture content of the leaves prior to the harvesting. Thus, it is crucial to consider the impact of seasonality on the quality of bamboo leaves when evaluating their suitability for ruminant nutrition. While high dry matter content can benefit ruminant nutrition, it is essential to ensure that it does not reduce palatability or limit nutrient availability, particularly nitrogen. Hence, monitoring the quality and accessibility of bamboo leaves is necessary to ensure optimal ruminant nutrition.

More so, the mean CP levels in the grasses in the current study confirmed the mean value of 70.0 g/kgDM noted for the majority of dry season pasture grasses reported in previous studies (Nori et al., 2009; Njidda, 2010; Gadberry, 2018), even though they were lower than the 100 g/kgDM threshold that Norton (1994) and Bhandari et al. (2015) reported as being the required CP threshold in pasture fodders to initiate voluntary intake in ruminants and below which rumen functions are significantly hampered. The lower CP levels in the grasses compared to the bamboo leaves suggest that the grasses may not be able to support high levels of animal productivity during the dry season without adequate protein supplementation. On the other hand, comparable to previous studies on similar bamboo species in the same ecological zone (Sasu et al., 2022, 2023), the CP levels of the bamboo leaves were found to be consistent. This suggests that bamboo leaves could be a reliable source of fodder for ruminants across dry seasons when the quality of grasses usually decreases, and feed scarcity is eminent. Again, the reported mean CP value of the bamboo leaves was higher than that of rice straws commonly fed to ruminants during the dry season, which has been reported to have a mean value of 50 g/kgDM (Babayemi and Adebayo, 2020). The implications of these findings are significant for ruminant nutrition, as they suggest that bamboo leaves could be a promising alternative to grasses and rice straws, which are commonly fed to ruminants. Furthermore, the higher nutritional value of bamboo leaves could help to address the nutritional disparities and high cell wall constituents associated with most pasture plants, especially grasses and crop residues during the dry season. By using bamboo leaves as fodder, farmers may be able to improve the nitrogen and fiber (bulk) content of their animal feeds and reduce the impact of feed scarcity on their livestock. In plants, fiber refers to the material that gives structure to the cell wall. Dietary fiber is composed of two structural carbohydrates—cellulose and hemicellulose—and a non-carbohydrate compound called lignin. Although lignin is not a carbohydrate, it binds to the structural carbohydrates and reduces their accessibility to rumen enzymes, making them less digestible. As plants age, their lignin content increases, resulting in less digestible fiber. Generally, the high fiber content in conventional diets for ruminants is usually linked with low protein concentrations, as observed for the grasses in this study. However, fiber content plays an important role in ruminant nutrition. In order to maintain healthy rumen function, ruminants require dietary fiber and its consumption triggers chewing, saliva production and rumination, which are important for proper digestion. Saliva contains sodium bicarbonate and phosphate salts (Humphrey and Williamson, 2001) which facilitates feed ingestion, and nutrient circulation, and represent an important pH buffer for ruminants, especially for cattle fed high-concentrate diets that promote rumen acidification (Ricci et al., 2021). In the current study, both bamboo leaves and the grasses were fibrous, thus, can enhance chewing and stimulate saliva to maintain the rumen pH required to prevent metabolic disorders in ruminants fed high-grain diets. Ruminal pH considerably affects cellulose degradation (Weimer, 2022). Our data showed that compared to the grasses, the bamboo leaves had relatively lower concentrations of cellulose (a less readily digestible plant cell wall component) and a higher level of hemicellulose (a more easily digestible fiber fraction). Thus, with the right pH condition in the rumen, bamboo leaves may provide better nutrition for certain animals compared to grasses. Thus, lower concentrations of cellulose and a higher level of hemicellulose in bamboo leaves may make them more easily broken down and absorbed in the digestive system of animals, which is especially important for herbivorous animals that rely on plant material as their primary source of nutrition. In addition, it was observed that the grasses exhibited a superior lignification profile, as indicated by their high acid detergent lignin (ADL) content when compared to the bamboo leaves. Lignin poses a challenge for rumen microbes to enzymatically break down, as it interacts with polysaccharides and proteins. Therefore, the relatively lower ADL content in bamboo leaves provides an advantage for rumen microbes to efficiently digest the soluble carbohydrates.

Furthermore, the authors noted that the fiber concentrations in the bamboo leaves were higher than those reported by Sasu et al. (2022) for similar bamboo species examined during the rainy season in the same geographical area. This discrepancy can be attributed to seasonality. Nonetheless, the fiber values in the bamboo leaves were higher than the levels needed for growing or fattening ruminants (150–200 g/kgDM) and high-producing dairy cows (250–280 g/kgDM). However, the values fell below the threshold of 700–800 g/kgDM, which, according to Mertens (1994), is required in the diet to cause voluntary feed intake in mature beef cows (Bos spp.). Notably, all bamboo species examined had acid detergent fiber (ADF) contents comparable to leguminous tree forages, which are considered high-quality forages with 350 g/kgDM ADF (Moore and Undersander, 2002). This suggests that bamboo leaves can effectively meet the National Research Council [National Research Council (NRC), 2001] recommendation of 300 g/kgDM neutral detergent fiber (NDF) in cow rations, with a minimum of 210 g/kgDM NDF supplied from other quality forage sources. However, since nutrient constraints and detoxification limitations have been proposed as alternative biological explanations for the varied diets among herbivores, it is important to consider the "nutrient constraints" or "nutrient complementation" hypothesis, which suggests that no single plant species can provide all the necessary nutrients in the right proportions for herbivores, and that dietary mixing is necessary to achieve a balanced nutrient intake (Westoby, 1974, 1978; Rapport, 1980; Distel et al., 2020). In line with this, bamboo leaves are not to be fed as the sole diet for ruminants, but rather be incorporated into a mixed diet to provide optimal nutrition for ingesting animals.

Finally, in terms of forage quality and its link to animal performance, high relative feed values are crucial (Babayemi and Adebayo, 2020). The bamboo leaves appeared to have a higher mean digestible dry matter compared to their grass counterparts, estimated at 57.5% and 52.9%, respectively. However, the value was notably lower than the mean value of 68.8% estimated for similar bamboo species in the same ecological zone during the rainy season reported by Sasu et al. (2022). This nutritional variation may be due to seasonal differences, as Agrovets Consultancy (1989) noted that the nutritional content of natural range fodders is often highest at the beginning of the rainy season and rapidly declines during the dry season.

Conclusion

This study provides insights into the nutritional composition of grasses and bamboo leaves and their potential as forage sources for ruminants during the dry season, which is a common period of feed scarcity. It compares the nutrient content of these Poaceae plants using different analytical methods and highlights the importance of their fiber content in ruminant nutrition. According to the analytical procedures and nutrient estimation equations utilized in this study, it was revealed that among the grasses, *Brachiaria decumbens* exhibited relatively higher nutritional characteristics followed by *Cenchrus purpureus* and *Megathyrsus maximus*. On the other hand, among the bamboo species, the leaves of *Bambusa vulgaris* had the highest nutritional characteristics, followed by *Oxytenanthera abyssinica* and *Bambusa balcooa*. A further comparison of results points toward the conclusion that bamboo leaves have a better nutritional profile than conventional grasses. Therefore, incorporating bamboo leaves into animal diets may increase productivity, particularly during the dry season when feed scarcity is common. Additionally, it was observed that the lower cellulose and higher hemicellulose concentrations in bamboo leaves may make them more easily broken down and absorbed in the rumen compared to the grasses. Therefore, bamboo leaves could be a reliable additive in grass-based ruminant diets and the diets of other herbivorous animals.

Gap

Although the study identifies the potential benefits of bamboo leaves as a forage source for ruminants in addition to the conventional grasses already available, it does not provide data on the specific nutrients especially minerals that contribute to the higher nutritional quality of bamboo leaves compared to grasses. Additionally, the study does provide data on the effects of bamboo leaves on animal performance, such as milk or meat production, and does not evaluate the economic feasibility of using bamboo leaves as a forage source. Therefore, further research could focus on identifying the specific nutrients in bamboo leaves that contribute to their higher nutritional quality, as well as the effects of bamboo leaves on animal performance and the economic viability of using bamboo leaves as a forage source. Additionally, future research could explore the effects of the leaves of different bamboo species and cultivars on ruminant nutrition, the optimal supplementation levels for ruminants fed *in vivo* with bamboo leaves, and the effects of different processing methods, such as ensiling, haymaking, chopping, and pelleting on the nutrient composition and digestibility of bamboo leaves. Lastly, further research could investigate the potential use of bamboo leaves as a source of bioactive compounds for animal health and production.

Data availability statement

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

Author contributions

PS conceptualized and designed the study and drafted the manuscript. OA, BA-M, DE, MK, and DO assisted in data collection. PS, VA-K, and BA-M analyzed and interpreted results. AA-J and AO assisted in data collection, analysis, and interpreted results. RA assisted in data analysis and interpreted results. All authors reviewed the results and approved the final version of the manuscript.

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Conflict of interest

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

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EDITED BY
Francis Tetteh,
Council for Scientific and Industrial Research (CSIR), Ghana

REVIEWED BY
Msafiri Mkonda,
Sokoine University of Agriculture, Tanzania
Rahmawaty Rahmawaty,
Universitas Sumatera Utara, Indonesia

*CORRESPONDENCE
Francis Kamau Muthoni
✉ fkmuthoni@gmail.com

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Extrapolation suitability index for sustainable vegetable cultivation in Babati district, Tanzania

Francis Kamau Muthoni[1]*, Jean Marc Delore[1,2], Philipo J. Lukumay[3] and Justus Ochieng[3]

[1]International Institute of Tropical Agriculture, NRM, Arusha, Tanzania, [2]Wageningen University and Research, Farm Systems Ecology Group, Wageningen, Netherlands, [3]The World Vegetable Center (AVRDC), Arusha, Tanzania

Land suitability assessment matches crop requirements with available resources to promote sustainable production. Scaling out of sustainable agricultural intensification practices to suitable biophysical and socio-economic conditions reduces the risk of failure and increases their adoption rate. This study applies a geospatial framework to identify potentially suitable sites for extrapolating two improved vegetable cultivars grown under integrated management practices (IMP's) in Babati District of Tanzania. On-farm trial data on the yield and income of two cultivars were used as a reference. Extrapolation was based on the gridded biophysical and socio-economic layers that limit the production of the two improved vegetable cultivars'. The extrapolation suitability index (ESI) showed the areas where cultivation of the two improved vegetable cultivars under IMP's can be scaled-out with a potentially low risk of failure. We generate maps of the most important limiting factor for each cultivar in every pixel to guide the spatial targeting of appropriate remedial measures. Application of these maps will promote evidence-based scaling out of improved vegetable technologies by the extension and development agencies.

KEYWORDS

digital agronomy, GIS, land suitability assessment, spatial targeting, recommendations domains, sustainable intensification, vegetable cultivars

1. Introduction

Vegetables are an essential dietary component as most are rich in micro-nutrients such as iron, Zinc, Magnesium, vitamins A and C (Ojiewo et al., 2010). These micro-nutrients play a vital role in human growth, development, and health. 90% of the population with Ca and Zn deficiency is in Africa and Asia (Kumssa et al., 2015). Efforts to increase the sustainable production and consumption of vegetables will significantly address malnutrition and hidden hunger. Moreover, vegetable farming promotes income diversification in small-scale farming systems in sub-Saharan Africa, thereby improving livelihoods.

The level of crop production is context-dependent. Recent research has shown that scaling out sustainable agricultural intensification technologies to locations with biophysical and socio-economic conditions similar to their trial sites increases their adoption rate and reduces the risk of failure (Annicchiarico et al., 2005; Rubiano et al., 2016). Yields attained at the reference agronomic trials can be achieved in other areas with similar biophysical and socio-economic conditions. Land suitability assessment is applied to identify locations with similar conditions to reference trial sites. Land suitability assessment promotes design of better land management by supporting land use pattern that prevents or avoids environmental degradation through the segregation of competing land uses (AbdelRahman et al., 2016; Han et al., 2021). Land suitability assessment improves knowledge on the appropriateness of specific land use in a location and identifies the limitation(s) hindering land utilization. Mapping the suitability of crops to the prevailing biophysical and socio-economic context informs evidence-based agricultural investments and promotes the sustainable use of limited resources. Characterizing the biophysical context under which technologies performed successfully is vital for planning to scale out investments.

Geospatial data and tools are applied to generate recommendation domains for sustainable agricultural intensification technologies as they offer the speed, flexibility, and power to synthesize big data on land resources (Hyman et al., 2013; Usha and Singh, 2013; Muthoni et al., 2019). Spatial frameworks for mapping crop suitability follow a 'top-down' or a 'bottom-up' approach. The top-down approach utilizes a multi-criteria analysis to classify remote sensing data into clusters based on predetermined criteria or expert knowledge but without direct reference to the on-farm trial sites (e.g., Tesfaye et al., 2015; Muthoni et al., 2017). The bottom-up approach utilizes data from field trials as the benchmark of the suitable environmental conditions for agronomic technology, followed by a spatial search of other areas with a similar context in the wider geographical area (Rubiano et al., 2016; Muthoni et al., 2019). The top-down approach is the most applied to generate the spatial recommendation domains for agronomic technologies (Tesfaye et al., 2015; Notenbaert et al., 2016), primarily due to the increasing free availability of gridded biophysical and socio-economic layers.

The bottom-up approach is not applied widely because of the limited data availability from on-farm trials. Recent studies have shown the potential of the bottom-up approach for developing extrapolation domains of bundles of technology options using available on-farm trial data (Rubiano et al., 2016; Muthoni et al., 2019). The "bottom-up" approach is more specific because recommendations are generated from on-farm trials after validation in multiple locations or seasons. Muthoni et al. (2019) developed the extrapolation suitability index (ESI) for maize varieties and mineral fertilizers in Tanzania. They combined data from agronomic trials and remote sensing layers to generate maps on the suitability of technology packages beyond the trial sites to guide scaling-out operations. The ESI method apply an innovative extrapolation detection algorithm (Mesgaran et al., 2014) that factors the dissimilarity from the reference trial sites while also accounting for novel combination of environmental variables beyond those encountered in the trials. Rubiano et al. (2016) mapped the global out-scaling of water-efficient rice technologies using data from 220 pilot sites. Annicchiarico et al. (2005) showed that scaling out Algerian durum wheat (*Triticum durum Desf.*) on GIS-generated recommendation domains had an 11% yield advantage.

There are few spatially explicit recommendations domains for vegetable cultivars worldwide. For example, Jayasinghe and Machida (2008) developed a web-GIS tool utilizing soil, topography, climate, and land use data to map land suitability for tomatoes and cabbages in Sri Lanka. In Nepal, Thapa et al. (2020) mapped the suitability of cauliflower, and Baniya et al. (2009) developed spatial recommendations for the larger cardamom (*Amomum subulatum Roxb.*). Ji et al. (2018) mapped the the spatial-temporal variability of vegetable production in China. Mostafiz et al. (2021) applied a fuzzy membership method to map suitability of vegetables between different seasons in Bangladesh. Other studies had applied a top-down multi-criteria decision making to map suitability of vegetables without on-farm trial data (Mugo et al., 2016; Mostafiz et al., 2021; Rahmawaty et al., 2021; Yuniarti et al., 2022; Zakaria et al., 2022). Although multiple agencies in Tanzania promote sustainable vegetable farming at scale, detailed maps on the suitability of improved cultivars and related improved agronomic practices are lacking.

A recent study in Babati district of Tanzania analyzed on-farm trials data to identify promising vegetable cultivars and related management practices (Lukumay et al., 2018). The study compared the yield response and economic benefits of improved tomato (*Lycopersicon esculentum*; "Tengeru 2010") and African eggplant (*Solanum aethiopicum*; "Tengeru White:) cultivars grown under improved management practices (IMPs) and standard farmer' practices (SFP's; control) (Lukumay et al., 2018). The IMPs comprised good quality seeds of improved cultivars, healthy seedlings, good agronomic practices (GAP's), and integrated pest management (IPM). The control plots used good-quality seeds and SFPs. Results from these on-farm trials revealed that growing the two cultivars using IMPs significantly increased yield for Tengeru 2010 tomato from 28 t ha^{-1} (control) to 64 t ha^{-1} and from 23.04 t ha^{-1} to 54 t ha^{-1} for African eggplant. Lukumay et al. (2018) further demonstrated that farmers who applied IMP's attained gross profit margins up to USD 18,300 and 9,600 ha^{-1} with benefit-cost ratios (BCR) of 8.5 and 4.5 for tomato and African eggplant, respectively. Evidently, the adoption of IMP in vegetable farming at scale could confer a broader societal impact in terms of yield and profits.

The question that emerged after the on-farm validation trials was where else should the package of two cultivars and IMP's be scaled-out with minimal risk of failure in Babati district of Tanzania? This study addresses the above question by conducting a spatially explicit characterization of biophysical and socio-economic contexts that match the trial sites where the improved vegetable technology packages returned significantly higher yield and income. We hypothesized that technological packages that show high yield potential in reference trial sites would also perform equally well in outlying areas with similar environmental conditions. The objective of our study is to produce a map of each cultivar's extrapolation suitability index (ESI) to identify areas where specific technological packages can be scaled-out with a potentially low risk of failure. Moreover, we generate a map showing the most important covariates (MIC) that highly limits each cultivar's suitability at every grid cell to guide the spatial targeting of appropriate remedial measures. The MIC analysis provides knowledge for localized targeting of management practices to improve the suitability of specific technologies. The spatially explicit framework presented in this paper will guide evidence-based land use planning for sustainable agricultural development in smallholder farming systems.

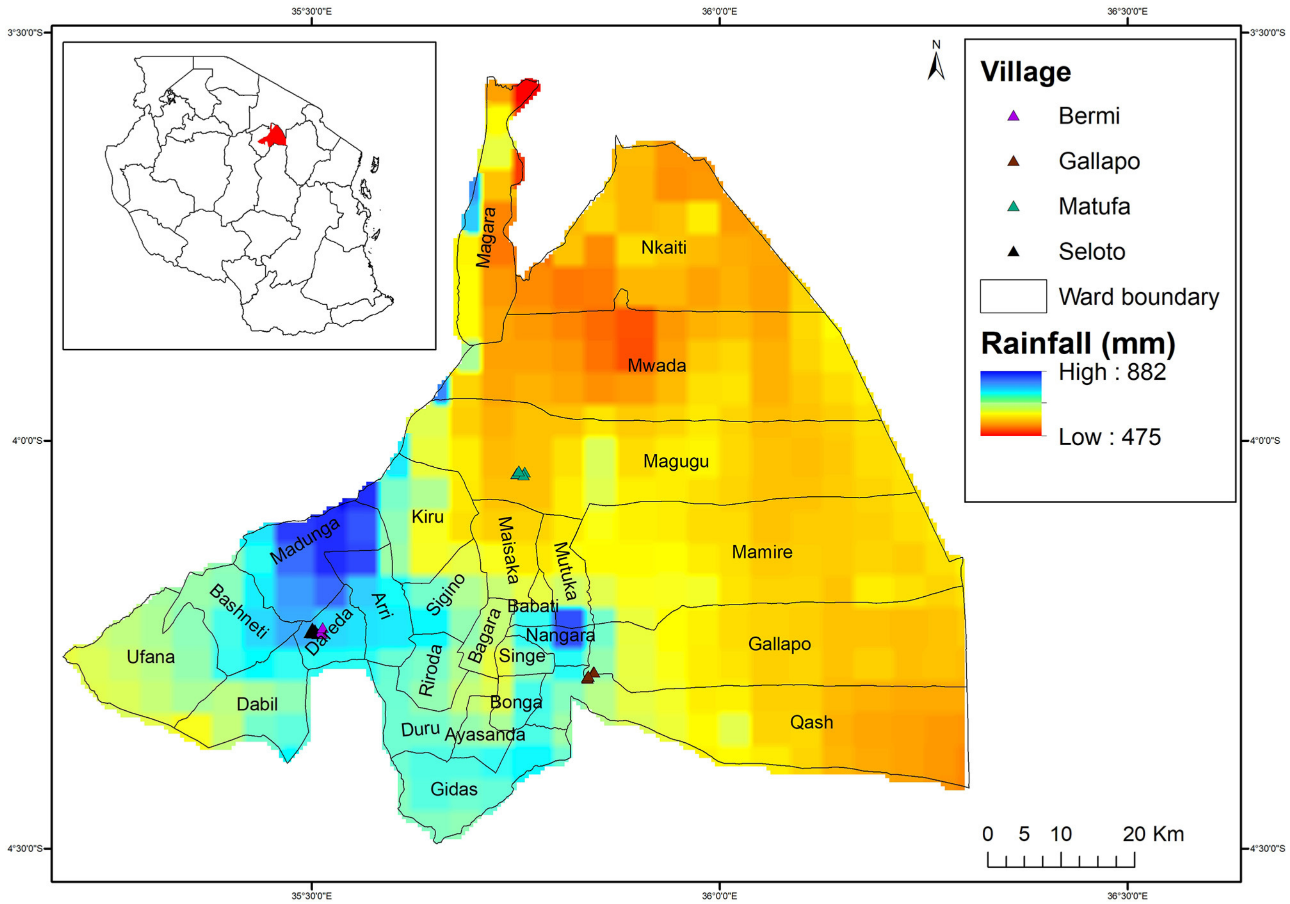

FIGURE 1
Location of Babati district and on-farm trial sites superimposed on the annual total rainfall obtained from TerraClimate database. This study utilizes knowledge gained from twenty-three ($n = 23$) on-farm trials conducted for two growing seasons (2013/14 and 2014/15).

2. Materials and methods

2.1. Study area

The study area islocated in Babati district of Tanzania (Figure 1). Maize-legume intercropping is the main farming system in the Babati district, but vegetables are grown to supplement income and nutrition. Livestock keeping mostly under zero-grazing systems is common and provides milk and farmyard manure. This study focuses on two vegetable cultivars; the tomato (*Lycopersicon esculentum*; "Tengeru 2010") and the African eggplant (*Solanum aethiopicum*; "Tengeru White"). The "Tengeru 2010" tomato is rated excellent for taste and high market acceptability and tolerate early blight, late blight, and tomato mosaic virus (Ojiewo et al., 2010; Minja et al., 2011). The "Tengeru White" African eggplant requires less water than tomatoes and prefers sunny conditions. It grows on a wide range of soils, including sandy loams but does not cope with waterlogging and intense shading. African eggplant is considered moderately sensitive to salinity and tolerant to acidity.

The on-farm trials were implemented to validate the suitability of baskets of technologies comprising an elite tomato ("Tengeru 2010") and African eggplant ("Tengeru White") grown under IMP's in the Babati District of Tanzania. The on-farm trials in a randomized complete block experimental design were implemented in four villages (Figure 1) characterized by high (Bermi, Seloto), medium (Gallapo), and low (Matufa) rainfall zones (Lukumay et al., 2018). The trial sites were selected based on agroecological potential (rainfall and altitude), population density, and market access under the Africa RISING program (https://africa-rising.net/). The results from the on-farm trials compared the yield and net benefits (profit) between the standard farmer's practice (control) and the integrated management practice (IMP) for the two cultivars. Lukumay et al. (2018) showed that the yield advantage and income for the IMP treatments of the two cultivars were more than double compared to the control (Figure 2). The IMPs package emerged as the best-bet for eggplant and tomato. The IMPs package comprised good quality elite seeds of improved vegetable cultivars, healthy seedlings, good agronomic practices (GAPs) and integrated pest management (IPM). GAPs included the application of manure, mulching, proper spacing, stalking, irrigation, and weeding. For tomato and eggplant, respectively, the IMP package produced a yield of 2.3 times higher and increased income by 1.6 compared to standard farmers' practice (Figure 2).

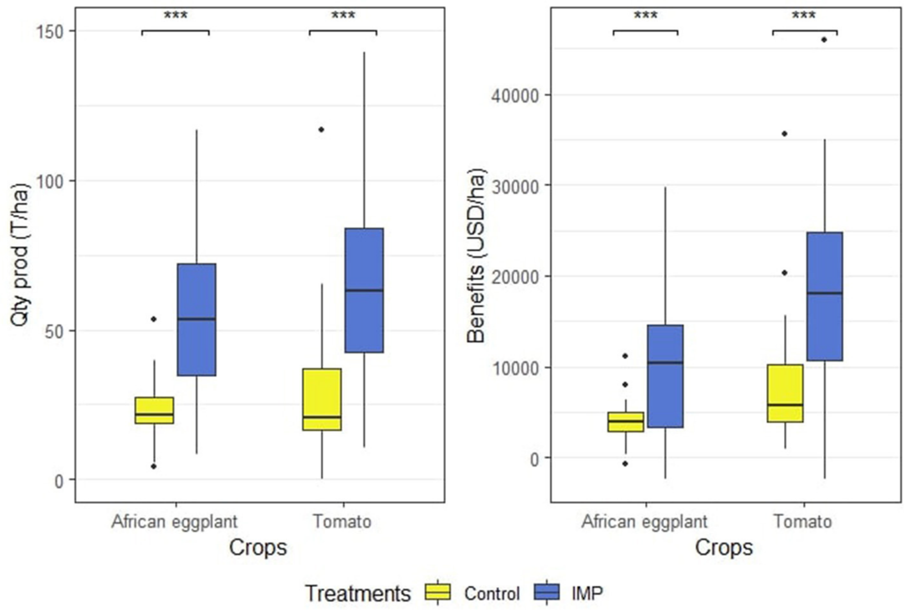

FIGURE 2
The yield and net benefits (income) for African eggplant (Tengeru White) and tomato (Tengeru 10) cultivars grown under standard farmers practice (control) and integrated management practices (IMP) in the Babati district of Tanzania.

2.2. Gridded biophysical and socio-economic datasets

We obtained a set of gridded biophysical and socio-economic layers that influence the suitability of the two vegetable cultivars from various sources (Table 1). The gridded datasets had different spatial resolutions ranging from 30 m (elevation) and 4 Km (climate). All gridded data was resampled to 30 meters resolution to avoid loss of high-resolution topographic details (Figure 3). The grid and vector layers representing the administrative boundaries were pre-processed, analyzed and visualized with the open-source R programming environment (R Core Team, 2023). The raster (Hijmans, 2023) and rasterVis (Lamigueiro and Hijmans, 2019) packages were mainly used for spatial analysis and visualization, respectively.

2.3. Statistical analysis

2.3.1. Site characterization

Data collected from on-farm trials were used to generate a map of the extrapolation suitability index (ESI) of a tomato ("*Tengeru 2010*") and the African eggplant ("*Tengeru White*") grown using IMP. Compared to SFPs, the treatments with IMP had a higher yield advantage and incomes. Therefore, the trial plots for IMP for both cultivars were selected as the reference sites when delineating the extrapolating suitability maps. A principal components analysis (PCA) was performed on a data frame containing the gridded environmental layers listed in Table 2 to identify the primary gradient associated with each trial site. The optimal number of clusters for environmental variables was determined using "NbClust" R package (Charrad et al., 2014). The package provides 30 indices for assessing the number of clusters. It proposes the best clustering scheme to the user from different results obtained by varying combinations of clusters, distance measures, and clustering methods. In our case, we evaluated the complete method with Euclidean distance for cluster sizes ranging from 2 to 15. Hierarchical clustering on principal components (HCPC) function of "FactorMinoR" R package (Lê et al., 2008) was utilized to group the trial sites into an optimal number of clusters with relatively similar environmental conditions. The cluster of trial sites' that each cultivar showed the highest mean yield and net-benefits was selected as a reference for extrapolation. A 30 m buffer around the location of best-performing trials was generated and used to crop the reference environmental layers. However, different criteria for selecting the best-bet trial sites can be specified: i.e., the yield stability, longevity of production, and quality of seeds; depending on the production objective.

2.3.2. Generating extrapolation suitability index

The method proposed by Muthoni et al. (2019) was applied to generate the ESI maps of the two vegetable cultivars grown under IMP. The ESI method utilize data from agronomic trials and remote sensing layers to generate maps on the suitability of particular technology package beyond the trial sites. The input variables were the points around the best-performing trial sites for each two cultivar in Babati and 11 gridded biophysical and socio-economic variables or their reasonable proxies that are known to affect growing and marketability of vegetable cultivars (Table 1). The trial sites where particular vegetable cultivar showed good performance were utilized as reference training sites. The ESI maps were generated by calculating environmental dissimilarity between

TABLE 1 Input variables for delineating extrapolation suitability index for vegetable technologies.

Abbreviation	Parameter	Original resolution	Source
Climatic			
Tmin	Annual mean minimum temperature (C°)	4 km	http://www.climatologylab.org/terraclimate.html
PPT	Annual precipitation (mm)	"	"
ETP	Evapotranspiration	"	"
Topographic			
DEM	Elevation (m)	30 m	https://asterweb.jpl.nasa.gov/gdem.asp
Slope	Slope (degrees)	30 m	Generated from DEM
Edaphic			
Sand	Sand content (%)	250 m	https://www.soilgrids.org
CEC	Cation Exchange Capacity (cmol$^+$/kg)	"	"
SOC	Soil organic carbon (fine earth) (g Kg^{-1})	"	"
pH	Soil pH	"	"
Socio-economic			
TotPop	Total human population	100 m	https://www.worldpop.org/
Market	Market access (distance in minutes)	1 Km	https://harvestchoice.org/

the reference trial sites and the outlying extrapolation area targeted for scaling out operations (Figure 1). This was accomplished by calculating novelty type-1 using the univariate extrapolation function in "ntbox" R package (Osorio-Olvera et al., 2020). The novelty type-1 ranges from 0 to negative infinity, with zero value representing the area that perfectly matches trial site conditions and, therefore, is the most suitable for scaling out. The most suitable zone in the projection domain that should be prioritized for scaling-out a particular agronomic technology package. This is the zone exhibiting the lowest univariate environmental dissimilarity compared to the conditions in the reference trial sites (novelty type-1 is equal or close to zero). The map of the novelty type-1 indicates the magnitude at which the environmental conditions at any particular location in the projection domains fall outside the range of values observed in the reference sites (Mesgaran et al., 2014). The most limiting covariate (MIC) was mapped using the ExeDet tool (Mesgaran et al., 2014). The most limiting factor at every location is the most extreme univariate value (minimum/maximum) compared to the reference sites' optimal conditions (Mesgaran et al., 2014).

3. Results

Three optimal clusters of environments were discriminated from the trial sites (Figure 4). The first two PCA axes explained 61.3% and 23.5% of the variance in environmental conditions, respectively. Cluster 1 represented trials in Matufa village characterized by lower agricultural potential due to warmer temperatures (high Tmin), sandy and alkaline soils (Figure 4). Cluster 2 had the highest trial plots ($n = 12$) located in Bermi and Seloto villages. The two villages have a high potential for agriculture as revealed by high elevation (DEM), precipitation (PPT), soil organic carbon (SOC), dense population (TotPop), and steeper slope; (Figure 4). Trials in cluster 3 were more correlated with the second PCA axis and represented trials in Galapo village characterized by high CEC and longer distance to the market.

The ESI maps revealed that the Tengeru 2010 tomato is widely adapted but more suitable in the southern-central area of the Babati district (Figure 6A). The African eggplant was particularly unsuitable in the humid highlands in the southwestern of the district (Figure 6B). The central area around Matufa village was the most suitable for Tengeru White eggplant.

Tengeru 2010 tomato cultivar's suitability in over 80% of the Babati district was limited by evapotranspiration (ETP; Figure 7A). Figure 8A shows that the median ETP (545 mm) in the projection domain was lower than the reference trial sites (618 mm). The DEM was the MIC covering the second largest area for Tengeru 2010 cultivar (Figure 7A); the median elevation in this area was higher (1,800 m) compared to the reference trial sites at 1,300 m above sea level (Figure 8B). The Tengeru White eggplant was primarily limited by precipitation (PPT) in over 70% of the district and the market access in the rest of the area located in the east to southeast of the Babati district (Figure 7B). Figure 8C shows that the median PPT (620 mm) was higher and more variable than the reference trial sites (580 mm). The south-east section of the district showed very low market access due to the longer time taken to reach the nearest market (Figure 8D).

4. Discussions

Maps on the extrapolation suitability index (ESI) were developed to guide evidence-based spatial targeting of two improved vegetable cultivars grown under IMP's in Babati district of Tanzania. Data from agronomic trials, and remote sensing layers were utilized to generate ESI maps showing a technology package's suitability beyond the trial sites. The ESI

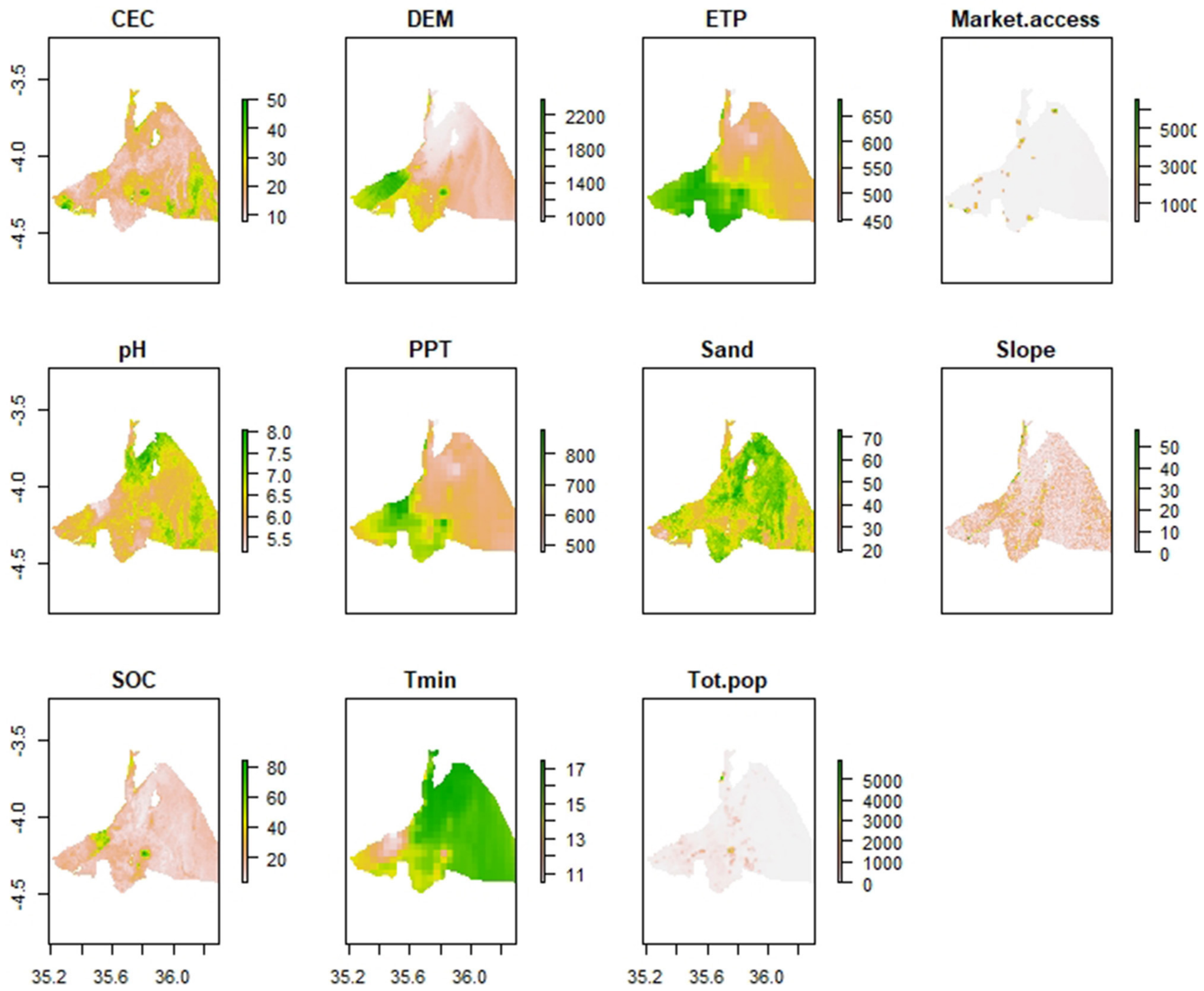

FIGURE 3
The input remote sensing layers representing the biophysical and socio-economic environment in Babati district. The abbreviations of the name are listed in Table 1.

maps highlighted the potential risk of scaling out the validated vegetable technologies outside the trial sites. The area with low ESI values (0–1) has a lower risk and is therefore identified as the highest priority recommendation domain for scaling out the two technology packages.

Characterizing the biophysical context under which technologies performed successfully is vital for planning the scaling out investments. It promotes the sustainable use of limited resources, e.g., targeting areas requiring minimal supplemental fertilizer and irrigation. Applying innovation presented in this paper in scaling-out programs is likely to reduce the risk of failure of technologies. Information presented in the ESI and MIC maps helps the extension and development agencies to rationalize investment given limited resources (Rubiano et al., 2016). The ESI map could help agro-input companies to target supplies to regions where their technologies are more suitable. The demand for improved seeds can be estimated before the planting season, thereby improving the input supply systems. The ESI maps can also guide agro-dealers to target suitable zones for disseminating specific agro-advisory services.

The approach leverages the increasing remote sensing data to drive evidence-based targeting of agricultural technologies in areas where long-term agronomic trials are lacking. The ESI and MIC maps can also be utilized to guide the setting up of multi-location trials to investigate the cultivars' local adaptations under different environments and management practices. A recent study in the same district identified the ability to adapt to local conditions as one of the critical drivers of adopting improved vegetables at scale (Gramzow et al., 2018). The maps on the ESI and the most limiting factor provide a factual basis for future surveys to unravel the socio-cultural conditions that limit technology adoption. These maps need continuous improvement as more data from on-farm trials and higher-resolution remote sensing data becomes available. Therefore,

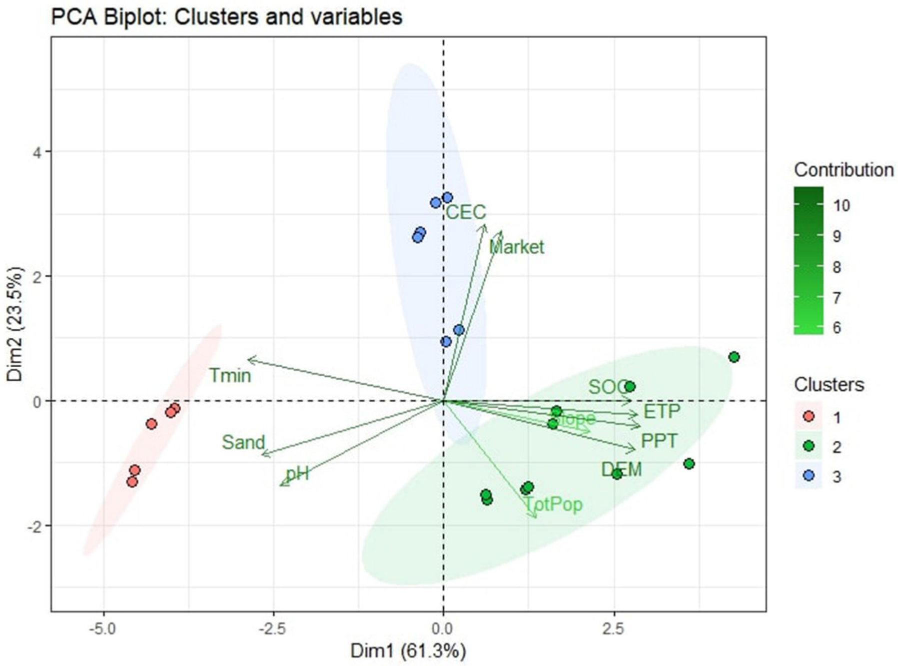

FIGURE 4
Characterization of the environmental conditions in the vegetable trials. Cluster 1 represents trials in Matufa village, cluster 2 are Bermi and Seloto and cluster 3 is Galapo. Trials in cluster 1 (Matufa village) and 3 (Galapo) showed the highest median yield (Qty Prod) and net benefit for the African eggplant and tomato, respectively (Figure 5). Therefore, trial plots located in the two best-performing clusters (1 and 3) were selected as the reference sites when delineating the extrapolating suitability maps for the two cultivars.

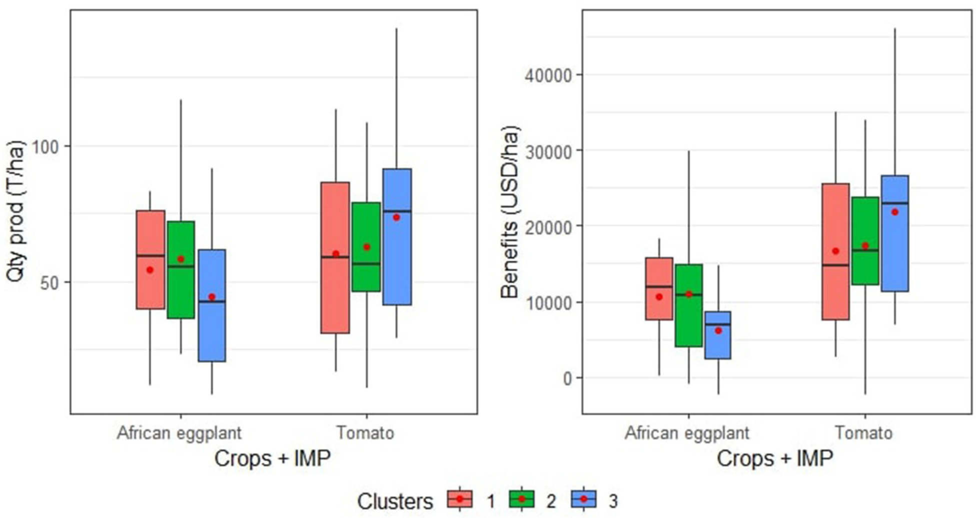

FIGURE 5
The yield (Qty prod) and net benefit variability for African eggplant (*Tengeru White*) and the tomato (*Tengeru 2010*) among the three environmental clusters. The red dots represent the mean of yield and benefits. Clusters 1 and 3 showed the highest yield and net benefit for African eggplant and *Tengeru 2010* tomato, respectively, and were used as the reference for spatial extrapolation.

the ESI maps are regarded as "living maps" that are updated as more information from trials becomes available to improve agro-advisory. For example, the recently released very high resolution (30 m) on soil nutrients and physical conditions (Hengl et al., 2021) will improve mapping crop suitability at the plot level Since this study utilizes open-source remote sensing data and geospatial tools, our methodology is replicable in other geographies or crops, if geotagged crop trial data is available. Although several institutions or initiatives are running vegetable trials in Tanzania, sharing data from these trials is a challenge. Initiatives for harmonizing agronomic trials remain a critical area of improvement.

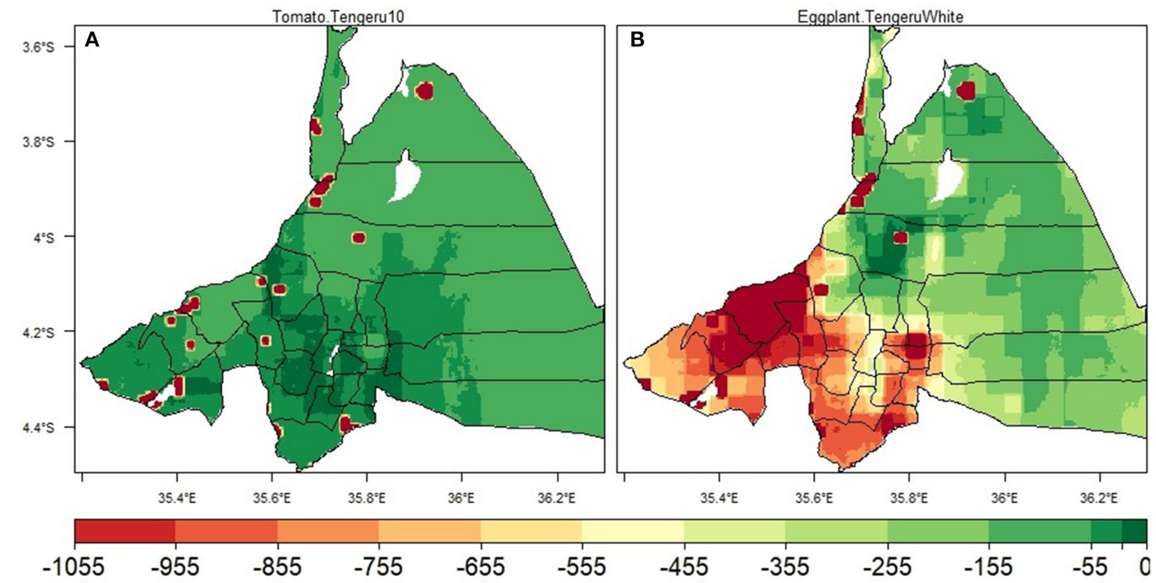

FIGURE 6
The extrapolation suitability index (ESI) for **(A)** tomato (*Tengeru 2010*) and **(B)** African eggplant (*Tengeru White*). ESI show the risk of scaling out vegetable cultivars grown under integrated management practices (IMP).

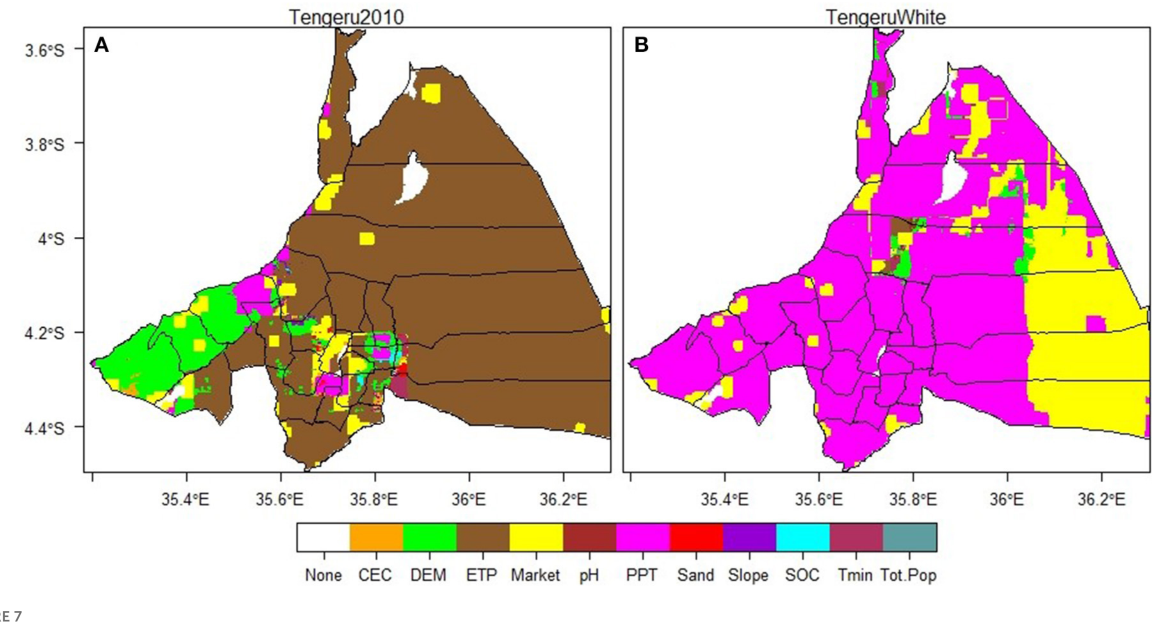

FIGURE 7
The spatial variation of the most important covariates (MIC) for two vegetable cultivars grown under improved management practices in Babati district. The zone where none of the covariates was identified as limiting represents vegetable cultivars' reference trial sites.

The ESI methodology can be adapted depending on the objective of the scaling operation. Different reference sites can be selected depending on the goal of the scaling initiative. We selected the reference trials in the villages that returned the highest yield and profit. Alternatively, a scaling operation can choose the sites with the lowest crop yield if the objective is to uplift productivity in most challenged farms. Similarly, the trials with the most stable yield across space and time could be selected even if the aim is to promote stability rather than increase crop productivity. Therefore, thorough site characterization, especially when setting the crop trials, is essential to ensure the representativeness of main environmental gradients.

The Tengeru 2010 tomato showed wide adaption to the Babati district's conditions, while the Tengeru White eggplant is unsuitable in southwest part of the district around Bermi and Seloto villages. The south-west area of Babati is characterized by humid

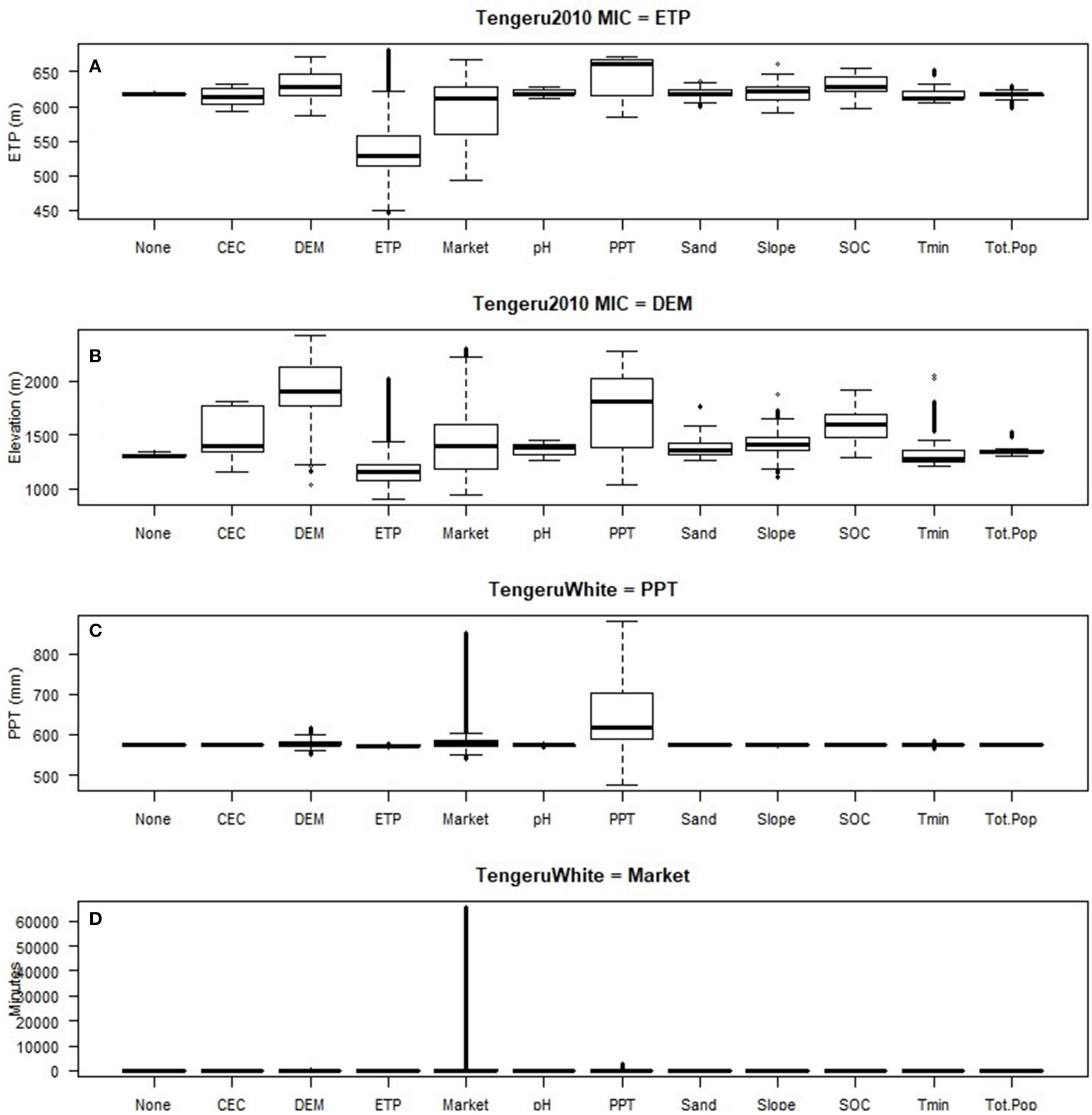

FIGURE 8
Boxplot of some of the most influential covariates (MIC) for the two vegetable cultivars in different Babati district zones. The MIC's for Tengeru 2010 are **(A)** evapotranspiration (ETP) and **(B)** elevation (DEM). MIC for Tengeru White eggplant are **(C)** precipitation (PPT) and **(D)** market access. The zone where none of the covariate was limiting represented the reference trial sites.

highlands and high precipitation (Figure 1). African eggplant requires less water than tomatoes and prefers sunny conditions like the situation around Matufa village that recorded the highest yields. Higher precipitation and lower evapotranspiration compared to the reference trial sites emerged as the main limiting factors in the large area for eggplant and tomatoes, respectively. This reflects the importance of optimal moisture for vegetable cultivation. Lower evapotranspiration than the reference sites limited tomatoes' suitability in the largest area. Since evapotranspiration is directly proportional to soil moisture content, it suggests that lower than optimal moisture affected the suitability of the tomatoes. Our study concurs with recent studies that observed that deviations from optimal soil moisture highly limit land suitability for vegetable cultivation in the tropics (Widiatmaka, 2016). However, too much rainfall increase the instances of pest attack on tomatoes thereby increasing the production cost since more pesticides are applied (Yuniarti et al., 2022). Low market access was the main factor limiting the Tengeru White eggplant's suitability in the hilly and forested landscape in south-east of the district. Although south-east of Babati district showed moderate to high suitability for African eggplant, poor accessibility can hinder vegetable production investments. Vegetables are durable commodities that need good market access to avoid post-harvest losses and high transport costs that reduce profits. Ji et al. (2018) reported road density as among China's most important drivers of vegetable production. Poor accessibility in south-east of Babati district is confounded by the prevalent lack of appropriate post-harvest storage management practices that cause up to 50% of yield losses of vegetables between harvesting and consumption (Majubwa et al., 2015).

The maps on the most influential covariates provide an evidence-based tool for spatial targeting of appropriate remedial measures. Evapotranspiration (ETP) and precipitation (PPT) were the main limiting factors for the two cultivars revealing that enhancing soil water conservation measures or supplemental irrigation is likely to increase yield.

However, our study did not consider the socio-cultural aspects that may hinder the adoption of a technology package even in ecologically suitable locations. There is a need to improve the ESI approach to capture the spatial variations of socio-cultural aspects like the differences in resource endowments, level of awareness, production orientation, and gender norms known to influence the adoption of vegetable technologies. For example, Fischer et al. (2020) reported that cultural norms restrict the participation of women in public gatherings leading to lower access to extension services. These norms in turn prevents women from getting more involved in fruit vegetable production and make them focus on leafy vegetables, as their cultivation is perceived easier and less costly. Similarly, Mugiyo et al. (2021) observed that the exclusion of crucial social-economic variables, such as access to credit and extension services, limits the adoption of vegetable cultivars in areas with suitable biophysical criteria. In that regard, Notenbaert et al. (2016) suggested the inclusion of socio-cultural variables in developing recommendation domains for agricultural technologies through stakeholder engagement and consultations. Nevertheless, the ESI maps provide a solid basis for future surveys to unravel the socio-cultural conditions that limit vegetable technologies' suitability.

Most studies on mapping the suitability of vegetables primarily utilized the top-down multi-criteria decision-making approaches that are subject to expert opinions (e.g., Widiatmaka, 2016; Rahmawaty et al., 2020, 2021; Mugiyo et al., 2021; Zakaria et al., 2022). In these studies, the geospatial layers were first classified into suitability groups based on literature or expert knowledge. Our method substantially reduces subjectivity by incorporating the reference crop trial data.

Future developments will focus on designing a open-source web-GIS tool for mapping the suitability of vegetable cultivars and agronomic practices. The proposed tool should be user-friendly and straightforward so farmers and village extension staff can operate it with basic gadgets with or without an internet connection to provide on and off-line agro-advisories. A similar web-GIS open-source tool implemented in Sri Lanka proved to be helpful to rural farmers with limited IT knowledge (Jayasinghe and Machida, 2008). The tool's utility was supported by the establishment of information technology centers in rural areas under a government project called e-Sri Lanka. This could be replicated in the Babati district to foster the vast potential of vegetable development. The targeting tool can be integrated into mobile-based agro-advisory initiatives currently piloted in the district.

4.1. Policy implications

The government of Tanzania and development partners has identified adoption of sustainable agriculture intensification technologies as a strategy to improve access to nutritious food. This aimed to achieve the sustainable development goal (SDG) 2 i.e., "end hunger, achieve food security and improved nutrition, and promote sustainable agriculture." The reduction of malnutrition, stunting, and wasting is a priority policy issue. Vegetables are rich in essential micro-nutrients (Ojiewo et al., 2010), therefore increased production, accessibility and consumption promotes healthy living by reducing the hidden hunger (malnutrition and stunting) especially in children under five and elderly (Khamis et al., 2019). Extension agencies in Tanzania promote growing elite varieties of fruits and vegetables to increase nutritional security and generate more income in smallholder farming systems (Ochieng et al., 2021). Moreover, promoting adoption of improved vegetables at scale is an essential policy toward increasing income for rural households. The ESI maps generated in this study enables the extension and development agencies to objectively identify the priority areas for better scaling out of improved vegetables.

5. Conclusion

This study presents maps on the extrapolation suitability index (ESI) and the most influential covariates (MIC) for two vegetable technology packages in the Babati District of Tanzania. These maps are a useful guide to extension and development partners on prioritizing sites for targeting scaling out intervention to increase yield, income and maintain environmental health. Maps generated from this study are further expected to reduce the risk of failure of improved vegetable packages and ultimately enhance adoption at scale. The information generated in this study will support decision making on allocation of land for diversified agricultural production to achieve food and nutrition security. The main advantage of the method is its replicability across space and time, low investment required, and generates easy to understand the maps. However, the accuracy of the maps is dependent on the precision of the input layers and therefore they need to be validated on the field before adoption by extension agencies.

Data availability statement

The agronomic data used in this manuscript is available upon request at https://doi.org/10.7910/DVN/GQGQR6. The remote sensing data applied in the manuscript are open source and are available in the repositories listed in Table 1.

Author contributions

PL and JO collected and curated agronomic data. FM and JD designed the study, collected remote sensing data, and analyzed the data. FM, JD, PL, and JO contributed to writing and review of 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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EDITED BY
Francis Tetteh,
Council for Scientific and Industrial Research (CSIR), Ghana

REVIEWED BY
Chrilukovian Wasike,
Maseno University, Kenya
A Amarender Reddy,
National Institute of Agricultural Extension Management (MANAGE), India

*CORRESPONDENCE
Shalander Kumar
✉ k.shalander@cgiar.org

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Potential for increasing groundnut production in Tanzania by enhancing technical efficiency: A stochastic meta-frontier analysis

Abhishek Das[1], Shalander Kumar[1]* and N. V. P. R. Ganga Rao[2]

[1]Enabling Systems Transformation, International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, Telangana, India, [2]Accelerated Crop Improvement, International Crops Research Institute for the Semi-Arid Tropics, Nairobi, Kenya

Groundnut crop is one of the major sources of financial and food security for a large number of Tanzanian smallholder farmers. However, the production of groundnuts in Tanzania is underdeveloped, and yields are reportedly 2.5 to 3 times lower than in other African nations such as Nigeria. There are a number of factors that contribute to lower yields including the cultivation of outdated plant varieties, increased climate variability, the infestation of pests and diseases, and the use of outdated farming techniques. To analyze the scope for increasing groundnut production, this study investigates and compares the technical efficiencies (TEs) and technological gap ratios (TGRs) in Tanzania's four main groundnut-producing regions, namely the Central zone, Lake Zone, Southern zone, Southern highland zone, by using a two-step meta frontier model. We used ICRISAT data collected under the Tropical Legume-III project during 2017–18. Our results show a very low level of technical efficiency of groundnut production in the regions and significant regional differences in TEs, TGRs, and Meta Technical Efficiencies (MTEs). The study identifies a tremendous scope to increase groundnut productivity and production in Tanzania by enhancing its production efficiency and the key drivers that may help harness this potential.

KEYWORDS

groundnut production, Tanzania, technical efficiency, stochastic meta-frontier, technology gap

1. Introduction

Groundnuts are the second-most significant crop after soya beans for the production of oil seeds, the thirteenth-most significant crop for human consumption, and the third-most significant crop for the production of edible vegetable oil (Taphee et al., 2015; Upadhyaya and Dwivedi, 2015). The groundnut seed is an excellent nutrient-dense food that provides a high percentage of high-quality vegetable oil (48–50%), as well as protein (26–28%), dietary fiber, minerals (Ca, P, Mg, Zn, and Fe), and vitamins (E, K, and B complex) (Janila et al., 2013), and parts of the crop (haulms) are used as livestock feed. More than a hundred different countries across the tropics, subtropics, and warm temperate zones around the world cultivate groundnuts (Upadhyaya et al., 2012). Despite the fact that the production of groundnuts in East Africa is characterized by low input, low productivity, and inadequate market access (Giliomee, 1994; Carr, 2001), it plays an important role in achieving food security among low-income rural households. Though the production of groundnuts in

African countries such as Tanzania takes place on a smaller scale under low input- low output systems (Taru et al., 2010) however it is one of the most significant crops for a large number of smallholder farmers in Tanzania and provides food, nutrition, and income for their households. Tanzania ranked 12th in groundnut production globally, producing 690,000 tons, 4% of Africa's production, and 1.29% of global production in 2020 (FAO, 2022). Tanzania's groundnut production is less developed than that of other African countries like Nigeria and Ethiopia, and Tanzania's yields are significantly lower than those of the other countries in the region. For example, in 2020, groundnut yield in the shell was 690 kg/ha in Tanzania, ranked 93rd, compared with 1,806 kg/ha in Ethiopia (38th) and 1,103 kg/ha in Nigeria (63rd) (FAO, 2022).

The groundnut yield in Tanzania has not increased substantially in the last couple of years; instead, it remained unstable. The groundnut production area (Figure 1) has increased by 754.7%, production by 1,226.92%, but yield increased by only 55.27% over 20 years from 2000 to 2020 [8]. However, the trends indicate that groundnut production is gaining importance in the country, but its growth is led by area growth, not productivity, thus a low efficiency of groundnut production.

The yield of groundnuts in Tanzania significantly differs not only among different cultivars, but also across the different agroecological zones (Tulole, 2010). The lower yield levels are particularly attributed to unreliable rainfall, diseases and pests, low seed replacement rate, low-yielding varieties, below optimum plant size and population, and outdated agronomic practices like fertilizer broadcasting (NARI, 2010). A low groundnut yield has consequences in terms of poor economic returns, food insecurity, and households' low income, which might affect the sustainability of groundnut cultivation and trapping the farmers in poverty (Tittonell and Giller, 2013). According to different studies, many biotic and abiotic stresses have resulted in Tanzania's low groundnut production (Reddy et al., 2003; Daudi et al., 2018). There is another set of studies where researchers have focused on farm evaluation of potentially high-yielding groundnut cultivars for adoption and adaptation in Tanzania (Tulole, 2010; Daudi et al., 2018; Mwalongo et al., 2020; Lukurugu et al., 2021). The majority of these research efforts have been focused on agricultural technology, groundnut diseases, improved varieties, the climatic conditions that restrict groundnut production, and the contribution of groundnut to household income for eradicating poverty. However, a little emphasis has been given on analyzing the socioeconomic factors that maybe restricting groundnut production and yield among smallholder farmers in Tanzania (Ramadhani et al., 2002; Mangasini et al., 2014; FAO, 2022).

We hardly found any studies addressing the farmers' efficiency of groundnut production in Tanzania. When we talk about efficiency, we're referring to technical efficiency (TE). This refers to the degree of efficiency to which the given inputs are utilized in order to achieve a certain level of output. A farm is considered to have a reasonably high level of technical efficiency if it is able to generate comparatively a greater output while utilizing a given level of inputs (land, labor, capital, and technology, etc.).

Using the stochastic meta-frontier model developed by Huang et al. (2014), this study aims to fill in this knowledge gap by analyzing the socioeconomic challenges faced by smallholder groundnut producers and evaluating the technical efficiency and technology gap ratio[1] of its production in various regions of Tanzania. This study analyzes socio-technical factors that limit the efficiency of groundnut production and generates evidence for policymakers at the local and national levels to develop short-and long-term policy responses to address the relevant constraints to improve the efficiency of groundnut production in Tanzania. This paper aims threefold: first is to identify the technical efficiency (TE) and technology gap ratio (TGR) of groundnut production for the four main zones of Tanzania, namely the central, lake, southern, and southern highland zones. Second, identify the factor that influences production and drives the inefficiency of groundnut production. Finally, determine the yield gap due to technical inefficiency and suggests required policy responses.

The rest of the paper is organized as follows. In Section 2, the theoretical model and methodology are described. Section 3 describes the data used and the variables. Following this, the results and discussion of empirical estimations are presented in Section 4. Finally, Section 5 discusses the conclusions and policy implications.

2. Materials and methods

We have used the meta frontier model to analyze the technical efficiency of Tanzania's groundnut production. The modern meta-frontier production function model was familiarized by Battese et al. (2004) and O'Donnell et al. (2008). Their model was estimated by a two-step process: In the first step, they estimated the group-specific frontier by using stochastic frontier (SF) regression. In the second step, they used mathematical programming. However, their second step has no statistical properties of the meta-frontier estimation results due to linear (or quadratic) programming algebraic calculation. Furthermore, no accounting for potentially different production environments facing firms (farm households) can be incorporated into the estimation, not to mention its incapability of isolating idiosyncratic shocks (Mwatawala and Kyaruzi, 2019). To overcome this problem, a new two-step SF method was developed by Huang et al. (2014) in order to estimate the group-specific frontiers and the meta-frontier, respectively, and to break down the various groups' efficiency scores into TE and TGs. The primary distinction between the new two-step SF approach and those of Battese et al. (2004) and O'Donnell et al. (2008) is that the former's second-step estimation of the meta-frontier is based on the SF framework rather than on a mathematical programming technique.

A general conventional stochastic production frontier model with j th production region and the i th decision making unit (DMU) or a firm in the t th period is given by:

$$Y_{jit} = f_t^j\left(X_{jit}\right) e^{V_{jit} - U_{jit}},\ j = 1,\ 2, \ldots\ldots J;\ i = 1, 2, \ldots\ldots N_j;\ t = 1, 2, \ldots\ldots,\ T \quad (1)$$

1 A production technology gap is a difference between the productivity achieved through the best technology represented in the meta frontier and the productivity achieved through chosen sub-technology represented in the group-specific frontier for a region. The technological gap ratio is the ratio of a certain farm's production frontier to the meta-frontier. (Mwatawala and Kyaruzi, 2019).

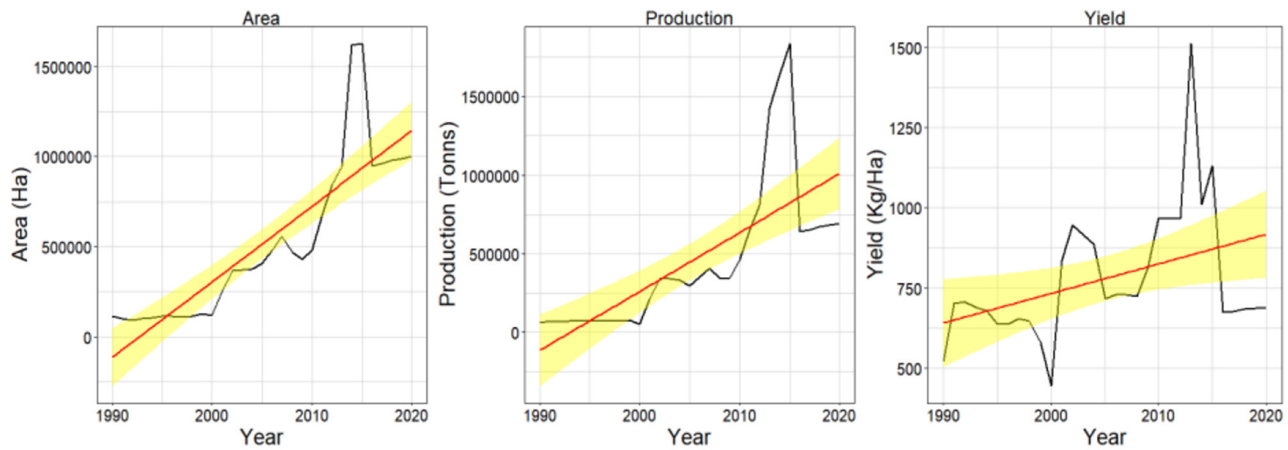

FIGURE 1
Trends in the groundnut production area, production, and yield in Tanzania from 1990 to 2020.

Where y_{jit} denotes the output level for farm i in the j th region in the t th period, X_{jit} is the input vector, V_{jit} represents the error term and is assumed to be iid as $V_{jit} \sim N(0, \sigma_v^{j2})$. U_{jit} representing technical inefficiency and is distributed as $U_{jit} \sim N^+\left(\mu^j\left(Z_{jit}\right), \sigma_u^{j2}\left(Z_{jit}\right)\right)$, i.e., truncated from below at zero and with the mode at $\mu^j\left(Z_{jit}\right)$, where Z_{jit}s are some exogenous variables. A firm's technical efficiency (TE) in production is then defined as:

$$TE_{it}^{j} = \frac{Y_{jit}}{f_t^j(X_{jit})e^{V_{jit}}} = e^{-U_{jit}} \quad (2)$$

We employ the methodology developed by Huang et al. (2014) to estimate the stochastic meta-frontier function that encompasses all the frontiers of the k regions. In step 2 we, specify the following SFA:

$$\hat{f}_t^j\left(X_{jit}\right) = f_t^M\left(X_{ijt}\right) e^{-U_{jit}^M}, \quad \forall\, j,\ i,\ t \quad (3)$$

where the $\hat{f}_t^j\left(X_{jit}\right)$ are the predictions from the group frontiers from step 1 in (1).

As discussed in detail in Huang et al. (2014), at a given input level X_{ijt}, the observed output Y_{jit} of the ith farm relative to the meta-frontier consists of three components, that is $\frac{Y_{jit}}{f_t^M(X_{jit})} = TGR_{it}^j \times TE_{it}^j \times e^{V_{jit}}$, where $TGR_{it}^j = \frac{f_t^j(X_{jit})}{f_t^M(X_{jit})}$ is technology gap ratio, $TE_{it}^j = \frac{f_t^j(X_{jit})e^{-U_{jit}}}{f_t^j(X_{jit})} = e^{-U_{jit}}$ is the firm's technical efficiency and $\frac{Y_{jit}}{f_t^M(X_{ijt})e^{-U_{jit}^M}} = e^{V_{jit}}$ is the random noise component.

Then, the two-step approach to estimating the meta-frontier as proposed by Huang et al. (2014) consists of two SFA regressions:

$$lnY_{jit} = \ln f_t^j\left(X_{ijt}\right) + V_{jit} - U_{jit},\ i = 1, 2, \ldots . N_j;\ t = 1, 2, \ldots\ldots, T \quad (4)$$

$$\ln\hat{f}_t^j\left(X_{jit}\right) = f_t^M\left(X_{ijt}\right) + V_{jit}^{M} - U_{jit}^M,\ \forall\, j,\ i,\ t = 1, 2, \ldots\ldots, J \quad (5)$$

Where $\ln\hat{f}_t^j\left(X_{jit}\right)$ is the estimates of the group-specific frontier from the first step in Equation (4). Since the estimates $\ln\hat{f}_t^j\left(X_{jit}\right)$ are group-specific, the regression (4) is estimated J times, one for each group (j = 1,2,. . . ,J). These estimates from all J groups are then pooled to estimate (5).

The meta-frontier should be larger than or equal to the group-specific frontier, i.e., $\hat{f}_t^j\left(X_{jit}\right) \geq f_t^M\left(X_{ijt}\right)$, due to the error of estimating $f_t^j\left(X_{ijt}\right)$. However, the metafrontier should be larger than or equal to the group-specific frontier, $f_t^j\left(X_{ijt}\right) \leq f_t^M\left(X_{ijt}\right)$. The estimated TGR must always be less than or equal to unity,

$$\widehat{TGR}_{it}^j = \hat{E}\left(e^{-U_{jit}^M} \middle| \hat{\varepsilon}_{jit}^M\right) \leq 1 \quad (6)$$

Where $\hat{\varepsilon}_{jit}^M = n\hat{f}_t^j\left(X_{jit}\right) - ln\hat{f}_t^M\left(X_{ijt}\right)$ are the estimated composite residuals of Equation (5). The TE of the ith farm to the meta-frontier is equal to the product of the estimate of the TGR in Equation (6) and the individual farm's estimated TE in Equation (2), that is,

$\widehat{MTE}_{it}^j = \widehat{TGR}_{it}^j \times \widehat{TE}_{it}^j$

In this study we used the Cobb-Douglas production function with cross-section data. The frontier (5) is specified as:

$$lnY_{ji} = \beta_{0j} + \sum_{m=1}^{5} \beta_{jm} ln\left(X_{jim}\right) + V_{ji} - U_{ji} \quad (7)$$

Where Y_{ji} is a vector of groundnut outputs, X_{jim} is a vector of inputs ($m = 1, 2, \ldots 0.5$) by farms ($i = 1, 2, \ldots .N$) and the Greek letters are parameters to be estimated. V_{ji} and U_{ji} are the random error term in the model.

3. Variables and data description

Our study covers four main groundnut producing areas of Tanzania: the Central, Lake, Southern, and Southern highland zones. Data were collected under the TL III project[2] during 2017–18 from 31 districts of the zones as mentioned earlier. In total of 702 randomly selected groundnut producing farm households from the four areas were surveyed under this project.

3.1. Main input and output variables

There are five input variables and one output variable in the data used in this analysis. Output includes annual groundnut production per household[3]. The output is measured in Kg. The Cobb–Douglas production function in the empirical model (7) is specified using the five input variables described next. Farmland use is defined as the size of productive land allocated to groundnut (both owned and rented) in acres; the seed is measured as the total seed (in kg) used in the production, and labor is measured as the total labor day used on the farm for groundnut production, including both family and hired labor. Fertilizer use (in kg)-di-ammonium phosphate (DAP) was used as fertilizer, and the number of oxen was used for plowing. Following Battese et al. (1996), O'Donnell et al. (2008), and Huang et al. (2014), we have used two dummy variables: D1 and D2 for fertilizer use and oxen use, respectively; D1 and D2 are 1 when fertilizer and ox are used in production otherwise 0 to deal with the zero observations for the fertilizer and oxen use input in the data set[4].

3.2. Environmental variable

Existing literature and discussion with stakeholders helped us to identify potentially important factors that were used to analyze the efficiency of groundnut production in Tanzania. The empirical study was carried out using a two-step process. During the first stage, a number of environmental variables were taken into consideration in the development of group-specific (regional) and industry-specific (overall) frontiers. This was done in order to investigate the influence that environmental factors have on the effectiveness of groundnut production and the technological gaps. In this analysis, environmental variables were broken down into household- and region-specific variables in order to better understand how they indirectly affect the effectiveness of groundnut production. The former variables were employed in the initial estimation of the group borders in Equation (4), which affects the firm specific (farm household) technical efficiency. On the other hand, the latter kinds of variables were used in the second-step estimation of the meta-frontier in Equation (5), which characterizes the environment that influences the selection of production technologies.

Discussion with stockholders, including researchers, development actors, and farmers, and reviewing existing literature, we considered five firm-specific environmental variables: the Farmer's experience of growing groundnut, the proportion of women participation in agricultural activity in the farm family, the average age of household, average education of household, participation in the technology transfer program. Moreover, we also considered the following three industry (region)-specific environmental variables: the past 10 years' average annual rainfall and market distance from the farm household and a dummy variable for average rainfall, 1 if the annual rainfall is up to 1,000 mm and 0 if it is greater than 1,000 mm.

Table 1 summarizes the sample statistics of four regions, including the output, inputs, and environmental variables for each region.

4. Results and discussion

Groundnut has been one of the most important crops in Tanzania as a source of livelihood and food security for smallholder farmers. However, groundnut production in the country has significantly increased over the past two decades; however, the yields have increased only marginally (Figure 1). The average yield of the Southern Zone, which was highest across zones, was 562 kg per ha, followed by Central Zone (472 kg/ha), Lake Zone (464 kg/ha), and Southern Highland Zone (457/ha) with an overall average 477 kg/ha (Table 2). These current groundnut yields are far lower than those obtained in other countries such as Ethiopia and Kenya, indicating a huge scope to increase the yield and bridge the gaps.

The meta-frontier analysis for estimating the technical efficiency of production is relevant only when different study regions use different technology. If the groundnut production data are collected from a single production frontier, implying that they adopt the same underlying technology, estimating the meta-frontier production function would be unnecessary. To determine whether or not the production frontiers in the four Tanzanian zones are distinct, we used the likelihood ratio (LR) test[5]. The total of the

2 The goal of the Tropical Legumes programmes was to increase the amount of legumes produced and assist smallholder farmers in improving their standard of living. The project was carried out in three stages: TL I (from 2007 to 2011), TL II (from 2012 to 2014), and TL III (2015–2019). The project's operations were carried out in Sub-Saharan Africa's Burkina Faso, Ghana, Mali, Niger, Nigeria, Senegal, Ethiopia, Kenya, Malawi, Mozambique, Tanzania, Uganda, and Zimbabwe as well as South Asia's India and Bangladesh. The International Center for Tropical Agriculture (CIAT), International Institute of Tropical Agriculture (IITA), and International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) worked with NARS partners to carry out this research, which was funded by the Bill & Melinda Gates Foundation. For more details, Available online at: https://www.icrisat.org/12-years-of-research-on-tropical-legumes/.

3 We added output from all the plots if a household has more than one plot.

4 Technically fertilizer use and oxen use data are not used directly in the model specifically, it is used in the form of $Ln(\max(fertilizer, 1-D1))$ for fertilizer and $Ln(\max(ox, 1-D2))$ for oxen use.

5 The LR statistic is defined by $\lambda = -2\left[\ln\left(\frac{L_{Ho}}{L_{H1}}\right)\right] = -2[\ln L_{Ho} - \ln L_{H1}]$, where $\ln L_{Ho}$ is the value of the log-likelihood function for the stochastic frontier estimated by pooling the data for all groups under the homoscedastic variance component, and $\ln L_{H1}$ is the sum of the values of the log-likelihood functions for the separate group frontiers (Battese et al., 1996, 2004; Rao and Coelli, 2004; Huang et al., 2014) with a Chi-square (χ^2) distribution with degrees of freedom $d = \sum_{j=1}^{J} \dim(\beta^j) - dim(\beta^M)$, where $dim(.)$ is the dimension of the parameter (Rao, 2004).

TABLE 1 Descriptive statistics for groundnut farmer in four regions and the whole sample.

		Output	Land	Seed	Labor	Fertilizer	Oxen use	Experience	Women participation	Average age of household	Average education of household	Average annual rainfall	Rain intensity
Central Zone	Min	32.00	0.20	6.38	3.60	0.00	0.00	0.00	0.00	17.00	0.00	0.00	703.63
	Max	1,950.00	16.00	727.89	170.98	35.00	10.00	70.00	1.00	81.00	10.33	120.00	1,070.09
	Mean	247.79	1.75	34.51	24.14	5.63	1.18	18.22	0.50	37.66	3.54	6.06	884.52
	SD	230.26	1.85	45.94	19.24	12.11	2.19	13.42	0.19	9.88	1.59	11.51	108.50
Lake Zone	Min	30.00	0.01	6.75	3.00	0.00	0.00	1.00	0.00	20.00	0.00	0.00	980.52
	Max	3,000.00	11.00	156.40	130.00	50.00	12.00	50.00	1.00	78.00	8.33	44.00	1,064.66
	Mean	325.61	2.00	41.17	23.45	7.85	1.93	14.01	0.48	39.00	3.20	4.99	1,008.85
	SD	385.11	1.54	26.87	16.92	14.37	3.06	11.46	0.17	11.49	1.47	6.04	25.06
Southern Zone	Min	52.00	0.25	5.03	5.50	0.00	0.00	1.00	0.17	23.00	0.75	0.00	1,276.26
	Max	929.00	6.00	260.75	58.33	50.00	6.00	42.00	1.00	58.50	7.20	25.00	1,347.42
	Mean	245.94	1.27	26.56	20.94	10.08	0.54	11.81	0.54	36.40	3.85	3.16	1,304.52
	SD	205.90	0.91	31.10	10.18	16.75	1.49	10.70	0.17	8.86	1.21	5.47	30.61
Southern Highland Zone	Min	25.00	0.25	6.00	5.27	0.00	0.00	1.00	0.00	20.00	0.00	0.20	824.67
	Max	740.00	8.00	86.46	85.00	50.00	6.00	42.00	0.83	72.00	7.50	150.00	1,267.55
	Mean	191.38	1.19	21.33	19.73	7.53	0.76	15.76	0.48	37.01	3.78	9.10	1,131.70
	SD	147.56	0.99	11.46	11.70	13.97	1.46	9.30	0.19	9.93	1.53	18.90	102.29
Overall	Min	25.00	0.01	5.03	3.00	0.00	0.00	0.00	0.00	17.00	0.00	0.00	703.63
	Max	3,000.00	16.00	727.89	170.98	50.00	12.00	70.00	1.00	81.00	10.33	150.00	1,347.42
	Mean	266.63	1.72	34.30	23.04	7.06	1.31	15.86	0.49	37.90	3.49	5.78	999.32
	SD	285.77	1.61	36.44	16.98	13.67	2.44	12.27	0.18	10.38	1.53	10.92	156.39

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TABLE 2 Yield (kg/ha) of four regions and for the whole sample.

Region	Obs.	Max	Min	SD	Average
Central zone	310	2,688.50	21.94	393.89	472.07
Lake zone	234	2,471.05	52.83	376.88	463.64
Southern zone	72	2,261.01	96.37	441.08	561.67
Southern highland zone	86	1,541.94	61.78	272.21	456.53
Overall	702	2,688.50	21.94	381.23	476.54

three log-likelihood function values reported in Table 3 represents the unrestricted log-likelihood function under the null hypothesis as −541.72, whereas the restricted value is −596.96. The degrees of freedom for the chi-square distribution was equal to 48, which is the difference between the numbers of parameters estimated under the two hypotheses, respectively. This leads to the likelihood ratio statistic of 110.49, twice the difference between the unrestricted and the restricted log-likelihood function values. Since the LR test statistic exceeds the associated critical value at the 0.1% level[6], the hypothesis is therefore absolutely rejected. This justifies the fact that the four regions are operating under heterogeneous technologies.

4.1. Input elasticities

Table 3 shows the estimation results[7] for the group-specific frontier function for four regions, the pooled data model, and the meta-frontier model. Input use for all four individual regions, pooled data, and meta frontier the models exhibit positive (except D1, D2, and land use of the southern zone), and more than 85% of the parameter's estimates are statistically significant at a 10% level.

The land use coefficient was positive and significant except southern zone ranging from 0.3116 in Lake Zone to −0.1275 (not significant) in the southern zone. These positive and significant results indicate that the higher the allocation of land for groundnut by the farm household, the higher would be the production per unit of inputs. This finding aligns with other studies (Huang and Lai, 2017) on Tanzania's groundnut production, possibly due to the economies of scale.

Among other partial production input elasticities fertilizer use in four regions of Tanzania, the pooled data, and the meta frontier, were the biggest, positive, and highly significant at a 1% level and it ranged from 1.0186 in the southern zone to 3.1006 in the lake zone. These results imply that the percentage change in fertilizer use would significantly influence groundnut production more than the other farm inputs. This study is in line with the findings of Taphe et al. (2015), who found a robustly positive correlation between the output of groundnut and the use of agrochemicals by small-scale farmers in the state of Taraba in Nigeria. However, the corresponding dummy D1 for fertilizer use was negatively significant. These two fertilizer results indicate that fertilizer use positively influences groundnuts' productivity. However, the way some Tanzanian farmers are applying fertilizer was not enhancing the production of groundnuts. Most of the smallholder groundnut farmers in Tanzania are using broad-casting methods of fertilizer application which not only increases the cost of production, but the effectiveness of fertilizer becomes low. The micro-dosing fertilizer application method could be one way to improve fertilizer use efficiency and groundnut productivity. Therefore, the capacity building of the farmers on appropriate methods of need-based fertilizer use, improving their access to fertilizers, and appropriate small machines for fertilizer application would contribute to increased productivity.

The estimated elasticity of groundnut production for seed usage was significant and positive across the zone, and it ranged from 0.1982 in the lake zone to 0.7542 in the Southern Highland zone. After fertilizer use, the seed was the 2nd most crucial factor for ground-nut production in Tanzania. This result is commensurate with Shamsudeen et al. (2011) and Taphe et al. (2015), which found groundnut quantity and seed quality as the essential input factor among the other input variables that increase groundnut output in Sub-Saharan Africa. An increase in the quantity of seeds sown increases the groundnut plant population per acre. A suitable variety and plant stand are especially significant in rainfed regions like Tanzania. This is because, as plant population increases, additional nuts are produced from the added groundnut plants while keeping other factors constant. However, in Tanzania, poor plant stand is often observed in the field mainly due to poor quality of seed and moisture deficit during germination. Moreover, the seed replacement rate was also very low. Most of the farmers have been using locally available low-quality seeds. Due to a lack of knowledge and the absence of a low-cost storage facility, farmers could not store the groundnut seed even if they had a good quality harvest; as a result, they ended up using poor-quality seed.

Labor use was positively significant in all zones, including pooled data and meta frontier, with values ranging from 0.1180 in the central zone to 0.4857 in the southern zone. Labor use was the 3rd most important factor for groundnut production in Tanzania. Since the major allocation of labor and land goes to maize and rice crops, additional labor to the groundnut crop will likely improve its productivity. The findings of Reddy and Bantilan (2012) and Danso-Abbeam et al. (2015) are consistent with our findings that there is a positive correlation between labor and groundnut production. In addition, Asekenye (2012) found that there was a positive correlation between groundnut production and the amount of labor used by groundnut farmers in Kenya. Some of the studies found a positive and not statistically significant relation between labor use and groundnut production in Uganda. On the contrary, some authors have also found a negative relationship between output and labor (Shamsudeen et al., 2011).

Oxen use was positive and significant (except lake zone and pooled data model, where the coefficient was positive but not significant). This finding, then, should be considered in the background of previous empirical investigations that revealed a favorable and significant influence of oxen power usage on output (Hailemariam, 2015; Abate et al., 2019). However, the corresponding dummy D2 was negatively significant (except lake

6 Table value of Chi-square (χ^2) distribution with degrees of freedom 48 at 0.1% level is 84.03.

7 We use the "frontier" package in R developed by Coelli and Henningsen (2013).

TABLE 3 Region-wise stochastic frontier estimates.

Variables	Central zone	Lake zone	Southern zone	Southern highland zone	Pooled data	Meta frontier
Constant_Input	5.9715 (0.6471)***	5.0187 (0.3620)***	2.8696 (0.3523)***	2.8068 (0.0130)***	4.7682 (0.2787)***	5.9962 (0.0462)***
Land use	0.1055 (0.0728)	0.3116 (0.0977)***	−0.1275 (0.1118)	0.2606 (0.0022)***	0.1379 (0.0528)***	0.1263 (0.0115)***
Seed use	0.2516 (0.0772)***	0.1982 (0.1160)*	0.5174 (0.0154)***	0.7542 (0.0129)***	0.3120 (0.0579)***	0.2366 (0.0119)***
Labor use	0.1180 (0.0477)**	0.3245 (0.0974)***	0.4857 (0.1164)***	0.2873 (0.0098)***	0.2454 (0.0494)***	0.1385 (0.0105)***
Fertilizer use	1.5620 (0.5781)***	3.1006 (0.4465)***	1.0186 (0.1164)***	1.6854 (0.2813)***	2.3031 (0.3166)***	2.1110 (0.0291)***
Oxen for plowing	0.2123 (0.1049)**	0.0395 (0.1102)	0.6605 (0.2082)***	0.2093 (0.1169)*	0.0959 (0.0679)	0.1111 (0.0142)***
Dummy for fertilizer use	−5.2846 (1.9799)***	−10.6666 (1.5648)***	−3.2551 (0.5754)***	−5.9035 (0.9661)***	−7.8626 (1.1028)***	−6.9755 (0.1007)***
Dummy for oxen use	−0.4384 (0.1415)***	−0.2125 (0.1608)	−1.0504 (0.4020)***	−0.3668 (0.1620)**	−0.2186 (0.0973)**	−0.2488 (0.0358)***
Constant_Environmental variables	2.6884 (0.5678)***	2.8116 (0.2333)***	2.3533 (0.4671)***	3.0573 (0.5222)***	2.3856 (0.1607)***	−3.2923 (0.4601)***
Exp. of growing groundnut	−0.0018 (0.0027)	−0.0098 (0.0054)*	0.0113 (0.0060)*	0.0090 (0.0157)	−0.0011 (0.0021)	xx
Proportion of women workers in family	−0.4763 (0.1899)**	−1.2764 (0.3699)***	−1.6342 (0.4925)***	−0.5507 (0.7130)	−0.9015 (0.1486)***	xx
Average age of HH	−0.0058 (0.0035)*	−0.0121 (0.0064)*	−0.0226 (0.0085)***	−0.0425 (0.0152)***	−0.0101 (0.0026)***	xx
Average education of HH	−0.0471 (0.0210)**	−0.0337 (0.0467)	−0.0313 (0.0563)	−0.1701 (0.0737)**	−0.0412 (0.0177)**	xx
Participation in tech transfer	−0.6596 (0.1046)***	−0.4975 (0.1348)***	−2,106.4000 (298.3300)***	−0.8183 (0.2942)***	−0.5421 (0.0755)***	xx
Distance to market	xx	xx	xx	xx	xx	0.0031 (0.0021)
Average annual rainfall	xx	xx	xx	xx	xx	0.0037 (0.0004)***
Dummy for rainfall up to 1000mm	xx	xx	xx	xx	xx	−0.3605 (0.1001)***
$\sigma_s^2 = \sigma_v^2 + \sigma_u^2$	0.3108 (0.0185)***	0.4386 (0.0706)***	0.2513 (0.0597)***	0.4457 (0.0539)***	0.3600 (0.0287)***	0.2060 (0.0222)***
$\gamma = \frac{\sigma_u^2}{\sigma_s^2}$	1.0000 (0.5443)*	1.0000 (0.0003)***	0.8965 (0.0602)***	1.0000 (0.0000)***	0.8794 (0.0695)***	0.9989 (0.0010)***
Log likelihood	−258.2932	−205.5292	−32.87101	−45.02341	−596.9618	6.6539
N	310	234	72	86	702	702

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. SDs are in the bracket. HH, Household head. Source: Authors' estimates based on primary data.

zone, where the sign was negative but not significant). These two results indicate that oxen use positively influenced groundnuts' productivity; however, it suggests a need for a more efficient allocation of oxen resources for groundnut production in all regions except the lake zone of Tanzania.

4.2. Technical efficiency, technology gap ratio, and meta technical efficiency

Table 4 reports the estimated TE Score, TGRs, and MTE scores for the four zones. Evidence from different studies of economic efficiency analysis suggests that worldwide, agricultural production achieves an average technical efficiency of around 70%. This value is significantly lower in many developing and underdeveloped countries (Bravo-Ureta and Pinheiro, 1993; Heshmati and Mulugeta, 1996; Seyoum et al., 1998; Sherlund et al., 2002; Linh, 2012). Our study of groundnut production in Tanzania found that the average group-specific TE score was very low, with an average mean TE score of 0.3035. This result implies that an average groundnut farmer produces 30.35% of the maximum possible (frontier) output, which the most efficient farmers produce in the study regions at a given level of input use. The implication of these results from the policy perspective is significant because,

TABLE 4 Summary statistics of various efficiency measure.

Measurement	Area	Max	Min	SD	Average
TE	Central Zone	0.9938	0.02286	0.1302	0.1815
	Lake Zone	0.9991	0.0221	0.1997	0.3053
	Southern Zone	0.9999	0.1253	0.2485	0.5494
	Southern Highland Zone	0.9999	0.0547	0.2616	0.5326
	Overall	0.9999	0.0221	0.2335	0.3035
TGR	Central Zone	1.0000	0.9399	0.0124	0.9869
	Lake Zone	1.0000	0.8508	0.0306	0.9219
	Southern Zone	0.8899	0.7288	0.0356	0.8162
	Southern Highland Zone	0.9255	0.6668	0.0537	0.8109
	Overall	1.0000	0.6668	0.0732	0.9268
MTE	Central Zone	0.9848	0.0224	0.1284	0.1790
	Lake Zone	0.9397	0.0214	0.1869	0.2822
	Southern Zone	0.8644	0.1067	0.2019	0.4473
	Southern Highland Zone	0.8657	0.0462	0.2136	0.4297
	Overall	0.9848	0.0214	0.1965	0.2717

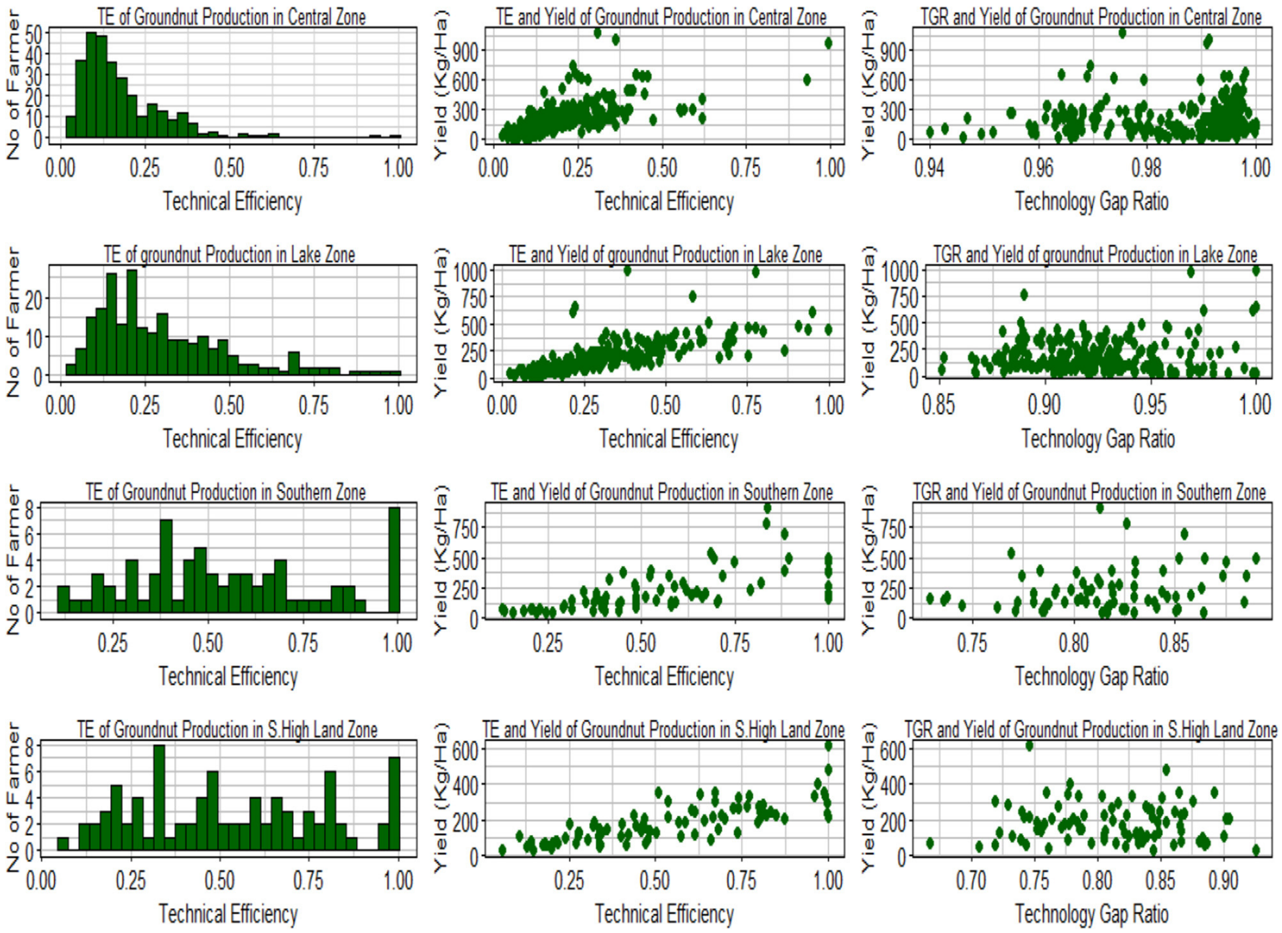

FIGURE 2
Distribution of technical efficiency (TE) and technical gap ratio (TGR).

TABLE 5 *T*-test for various efficiency measurements across regions.

Test	Group TE	TGR	MTE
Central Zone vs. Lake Zone	−8.2536***	29.769***	−7.2499***
Central Zone vs. Southern Zone	−12.18***	40.133***	−10.779***
Central Zone vs. Southern Highland Zone	−12.039***	30.198***	−10.373***
Lake Zone vs. Southern Zone	−7.6135***	23.148***	−6.171***
Lake Zone Vs. Southern Highland Zone	−7.3115***	18.44***	−5.6554***
Southern Zone vs. Southern Highland Zone	0.41537	0.74545	0.53103

***, **, and * denote significance at the 1%, 5%, and 10% levels respectively. Source: Process by authors.

on average, farmers could increase their output by around 70% if all farmers become technically efficient, or they could produce the same output level with a much lower level of input use under the present situation. The average group-specific TE score was highest for the southern zone at 0.5494, ranging from 0.1253 to 0.9999, followed by the southern highland with an average score of 0.5326 ranging from 0.0547 to 0.9999, the lake zone region with an average score of 0.3053 ranging from 0.0220 to 0.9991, and lastly, the central zone had the least TE score of 0.1815 ranging from 0.0229 to 0.9938. The LR test for our model implies that farmers in the different regions do not use the same underlying technologies, and also, the average TE scores of these regions are quite low, ranging from 0.1815 to 0.5494. This result implies that most groundnut farmers lag far behind the technically efficient farmer producers in their region due to poor adoption of technologies and improved practices of production (Figure 2).

The stochastic meta frontier (SMF) estimates the mean value of the technology gap ratio (TGR) score was 0.9268 ranging from 0.6668 to 0.9870, which is not close to 1. A TGR value of 1 denotes a position or circumstance in which the individual regional frontier and the meta-frontier are coincident. It denotes a circumstance in which the most productive farmers in a certain area perform at a level comparable to the most productive farmers on a global (country) scale. A lower average value of TGR and its wider range across zones indicates a substantial difference in the level of technology use among the zones. The Central Zone had an average TGR of 0.9869, ranging from 0.9399 to 1, followed by the Lake Zone, Southern Zone, and Southern Highland Zone, where the average TGR is 0.9219, 0.8162, and 0.8109, respectively. The highest average TGR value for the Central Zone 0.9869 indicates that some farmers in the Central Zone were the technically most efficient farmers across all the zones and produce maximum output per unit of input at the current level of technology as indicated by the meta-frontier (Figure 2). However, its average TE score of 0.1815 was the lowest among the study zones. This shows a big scope for farmers to farmers learning and extensions not only within the zone but also across zones.

The relative MTE scores for different zones were similar to group-specific TE scores. The overall average MTE score is 0.2717 ranging from 0.0214 to 0.9842, which was very low. Overall, Southern Zone was more technically efficient than Southern Highland Zone, Lake Zone, and central zone in producing groundnut in Tanzania as measured by the MTE.

Although the LR test indicates that the four zones are not using the same technology. To examine whether the difference among the efficiency scores across four zones is statistically significant, we calculated the t statistics with the null hypothesis that there is no true mean difference. Based on the values of t statistics the null hypothesis was rejected at the 1% level (except Southern Zone vs. Southern Highland Zone are not significantly different). Thus, it is evident that all technical efficiency scores are not similar across zones (Table 5).

4.3. Determinants of firm and zone-specific efficiency

Table 3 summarizes the farm- and zone-specific technical inefficiency estimates as determined by various environmental variables. If an environmental variable has a negative (positive) coefficient, it suggests that the variable has a positive (negative) influence on the level of technical efficiency.

The farming experience was found to have a mixed sign; only in the Lake Zone did the experience of growing groundnut significantly positively influence the efficiency of groundnut production. However, in the southern zone, the experience of growing groundnut has negatively influenced the efficiency of groundnut production. The empirical evidence from the present study indicates that the farmers' experience of groundnut crop production might not always be an important factor influencing the efficiency of production especially when a crop is cultivated by a large number of farmers in the region/country such as groundnut in Tanzania. That allows the farmers to often learn from their peers. Similar finding was also reported by Kumar et al. (2022) while investigating efficiency of chickpea production in Ethiopia.

Both men and women cultivate and manage groundnut production in the country; however, the production of groundnuts relies heavily on women as the primary source of labor (Tulole, 2010). According to our findings, there is a strong and positive correlation between efficiency and the proportion of women participating in groundnut production. The coefficient estimates for the corresponding variable for all the regions and pooled data are negatively significant (except for the southern highland zone, where the sign is negative but not significant). This result indicates that the farms with the higher number of female participants in groundnut production had significantly higher technical production efficiency. Increased participation of women workers in groundnut production improves technical efficiency in the study areas. The men might have prioritized their time for dominant crops such as maize and rice, and they are often also involved in multiple off-farm activities, and greater engagement of family women might have helped in the timely completion of various groundnut production operations. Similar results have been shown in chickpea production in Ethiopia (Kumar et al., 2022).

The average age of the household members comes out with a significant negative effect on inefficiency; therefore, it could be interpreted as higher average age having a positive influence on on-farm production efficiency. We have considered the age as the average of the family members older than 18 years. This might be due to the low participation of younger members in groundnut production. Therefore, those households with a higher proportion of younger members may likely be relatively inefficient. These results are similar to other previous studies (Khan et al., 2022).

Formal education was found to have significantly enhanced the efficiency of groundnut production. Farmers with more education may have had easier access to and utilization of pertinent information from a variety of sources about crop production technology, inputs, prices, and market demand. The educated farmers were thus technically more efficient than those who did not attain education. These results agree with the other research work (Ali and Khan, 2014; Kebede et al., 2014; Mahgoup et al., 2017; Alemu et al., 2018; Dessale, 2019), which found a positive relationship between technical efficiency and years of education. According to the findings of these research, a rise in human capital boosts agricultural output. This is because farmers with higher levels of education are more innovative; they are better able to recognize, analyze, and react to new information; and they are better able to adopt newer technology, such as fertilizers, pesticides, planting materials, and improved agronomic methods much more quickly than their less educated counterparts.

Lastly, the training and participation of farmers in the technology dissemination program strongly and positively influenced groundnut production efficiency with high significance for all the zones and pooled data. This finding is supported by similar other studies undertaken in Sub Saharan Africa (Dibba et al., 2018; Anang et al., 2022). This finding shows the relevance of research and agricultural advisory services in enhancing groundnut production in Tanzania. It also highlights the necessity for policy assistance to create appropriate participatory technology development and dissemination initiatives to bridge yield gaps in groundnut to contribute to food security.

We also assessed region-specific determinants of technical efficiency. The market distance from the farmers' agricultural fields, average rainfall, and a dummy variable for rainfall[8] up to 1,000 mm per year as one and zero otherwise. Distance to market from the agricultural field shows positive but not significant, implying shorter distance positively influences efficiency. Average rainfall shows positive and significant, implying that higher rainfall will badly affect groundnut production and efficiency in Tanzania. The negative influence of rainfall may be due to the negative impact of heavy rainfall events on groundnut production. This relationship was more clearly revealed from the dummy variable for rainfall up to 1,000 mm, which indicated that the zones with rainfall up to 1,000 mm per annum attained higher efficiency of groundnut production compared to higher rainfall regions. Although the groundnut is cultivated in Tanzania in the regions that have annual rainfall between 450 mm to 1,200 mm. However, the present evidence indicating a low efficiency of groundnut production in the region with more than 1,000 mm annual rainfall might be due to occurrence of water logging that may have adverse effect on yields (Tian et al., 2021).

5. Conclusion and policy implication

This study of technical efficiency analysis using the stochastic meta-frontier approach[9] clearly shows that a large proportion of Tanzanian groundnut farmers were producing much lower outputs from a given level of inputs use or using more inputs to get the same level of output, compared to the best performing farmers in their respective zones. The evidence shows that groundnut farmers in all four zones were using available groundnut production technology sub-optimally at around a 30% level of technical efficiency. At the same time, the maximum value of TGR is 1 for the central zone, and the lake zone indicates that some farmers in these two zones, which on average were least technically efficient, were producing groundnut at their optimum level concerning the meta frontier. As a result, there is a tremendous opportunity to increase groundnut production in these zones by approximately twice as much if the technical efficiency of crop production can be improved. There is a need for a different strategy for the Central and Lake zones, where the majority of the farmers are least efficient in groundnut production, and the Southern and the southern highland zones, where farmers are relatively more efficient in groundnut production, may be willing to make more investment on groundnut technologies. According to our findings, improving the effectiveness of Tanzania's groundnut production might be accomplished by reorienting gender priorities at the farm level within the traditional framework of a male-dominated extension system. To increase groundnut production sustainably, it is necessary to refocus training efforts on women and conduct training that is gender-friendly (by modifying the approach, time, and location of training). Knowledge-based interventions that support women farmers and educate them on how much and how to apply each type of input would help Tanzania realize its full potential in groundnut production. Enabling farmers' participation in technology dissemination programs was a key factor in enhancing the efficiency of groundnut production in all the zones. Therefore, the policy supports the design of appropriate participatory technology development and dissemination programs that can significantly contribute to bridging the yield gaps in groundnut crops in the country. Other significant elements that contribute to enhancing output performance include access to manpower, small agricultural machinery, and oxen. To increase groundnut output, farmers' access to better seeds and fertilizers was crucial. However, there is a need to improve farmers' awareness of the proper use of fertilizers. Encouraging farmer or community-level seed production together with appropriate lowest-cost storage systems such as hermetic bags or structures could be one of the effective strategies for enhancing the access and adoption of improved cultivars. There is a need to undertake a crop suitability analysis; the zones with annual

8 Annual rainfall required for groundnut production in Tanzania is 750-1,200 mm depending on the soil types and drainability.

9 Production frontiers are defined by the model and within the sample values. This implies that there may be techniques of production not practiced by any of the farmers in the sample, which could yield a much higher output for the same input level.

rainfall up to 1,000 mm were found to be more efficient; therefore, the high rainfall region should get low priority for groundnut production. It is possible to increase the efficiency of groundnut production to a great extent by expanding farmers' access to improved seeds, providing extension support that is need-based and gender-responsive, and encouraging farmers to participate in programmes that develop new technologies.

Though there were no significant variations in the average groundnut yield in four zones, we found a significant difference in TEs across regions. Following Moreira and Bravo-Ureta (2010), it may be suggested that adaptive research for development may provide the best outcomes for the less efficient areas/farmers far away from the meta frontiers. The research that helps in adapting the improved technologies and practices from the better performing areas and zones may contribute to increased efficiency of production. This would be a rational course of action to take in order to facilitate advancement toward the Meta Frontier. This would need strengthening of the agricultural extension system by improving the knowledge of the extension partners on different aspects of the groundnut value chain. And the policies are needed that provide incentives for the dissemination of accessible technology to remote places and farmers with low efficiency. It also emerges from the study that encouraging "farmer to farmer" extension that enables sharing of learnings and knowledge of the efficient farmers available in each zone, would considerably improve Tanzania's groundnut production efficiency.

Data availability statement

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

Author contributions

AD: conceptualization, methodology, validation, coding, formal analysis, investigation, data curation, and writing—original draft. SK: conceptualization, writing—review and editing, supervision, project administration, and funding acquisition. NG: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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

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One Acre Fund, Rwanda

*CORRESPONDENCE
Adane H. Tufa
a.tufa@cgiar.org

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

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Analysis of adoption of conservation agriculture practices in southern Africa: mixed-methods approach

Adane H. Tufa[1*†], Joseph S. Kanyamuka[1†], Arega Alene[2], Hambulo Ngoma[3], Paswel P. Marenya[4], Christian Thierfelder[3], Happy Banda[1] and David Chikoye[5]

[1]Department of Socioeconomics and Agribusiness, International Institute of Tropical Agriculture, Lilongwe, Malawi, [2]Department of Socioeconomics and Agribusiness, International Institute of Tropical Agriculture, Nairobi, Kenya, [3]Department of Sustainable Agri-Food Systems, International Maize and Wheat Improvement Centre (CIMMYT), Harare, Zimbabwe, [4]Department of Sustainable Agri-Food Systems, The International Maize and Wheat Improvement Center (CIMMYT), Nairobi, Kenya, [5]Department Plant Health and Nutrition, International Institute of Tropical Agriculture (Zambia), Lusaka, Zambia

In southern Africa, conservation agriculture (CA) has been promoted to address low agricultural productivity, food insecurity, and land degradation. However, despite significant experimental evidence on the agronomic and economic benefits of CA and large scale investments by the donor community and national governments, adoption rates among smallholders remain below expectation. The main objective of this research project was thus to investigate why previous efforts and investments to scale CA technologies and practices in southern Africa have not led to widespread adoption. The paper applies a multivariate probit model and other methods to survey data from 4,373 households and 278 focus groups to identify the drivers and barriers of CA adoption in Malawi, Zambia, and Zimbabwe. The results show that declining soil fertility is a major constraint to maize production in Zambia and Malawi, and drought/heat is more pronounced in Zimbabwe. We also find gaps between (a) awareness and adoption, (b) training and adoption, and (c) demonstration and adoption rates of CA practices in all three countries. The gaps are much bigger between awareness and adoption and much smaller between hosting demonstration and adoption, suggesting that much of the awareness of CA practices has not translated to greater adoption. Training and demonstrations are better conduits to enhance adoption than mere awareness creation. Therefore, demonstrating the applications and benefits of CA practices is critical for promoting CA practices in all countries. Besides, greater adoption of CA practices requires enhancing farmers' access to inputs, addressing drudgery associated with CA implementation, enhancing farmers' technical know-how, and enacting and enforcing community bylaws regarding livestock grazing and wildfires. The paper concludes by discussing the implications for policy and investments in CA promotion.

KEYWORDS

conservation agriculture, climate change, climate adaptation, adoption, focus group discussion, Malawi, Zambia, Zimbabwe

1. Introduction

Poor soil fertility and drought are the major constraints to maize production in southern Africa. According to Omuto and Vargas (2018), there is a high prevalence of soil degradation linked to inadequate soil fertility management, fragile soils, steep slopes, limited extension services, low level of awareness and poor adoption of soil conservation technologies, erratic and high rainfall intensities, and little soil cover. Moreover, the effects of climate change and population growth further threaten the livelihoods of millions of farmers in the region (Lobell et al., 2008; Sanginga and Woomer, 2009). The increased threats of climate change, soil fertility decline, and pressure on food and nutrition security require transforming the current farming systems into more robust ones based on good agronomy and conservation agriculture (CA)[1] (Giller et al., 2015; Thierfelder et al., 2017). Improved seeds and mineral fertilizers alone are insufficient: improved maize and legume varieties and improved and more sustainable land-use practices—particularly those that increase water and nutrient capture—are imperative. Adaptation to a changing climate requires new and innovative solutions at the field, farm, and community levels; and at different intensities (Cairns et al., 2012). CA has increasingly been promoted in southern Africa to address many problems associated with conventional agriculture, including soil degradation, high labor demands, and drought. As a practice, CA addresses low soil fertility, moisture deficits, and low management standards through the use of soil-fertility-enhancing technologies (precision fertilizer application, crop rotations, sequencing, and interactions), improved moisture use efficiency, and higher standards of agronomic management practices (Marongwe et al., 2011; Mafongoya et al., 2016; Madembo et al., 2020).

However, in southern Africa, the adoption rate of CA practices is below expectation, despite significant experimental evidence on the agronomic and economic benefits of CA and significant investments by the donor community and national governments in the region. Recent evidence shows slow and, at times, dis-adoption of this promising technology (Mazvimavi and Twomlow, 2009; Arslan et al., 2014; Pedzisa et al., 2015a; Grabowski et al., 2016; Brown et al., 2017; Ng'ombe et al., 2017; Tambo and Kirui, 2021). Farmers who implement CA often do not practice all three CA principles in all cropping cycles and on all their plots. In sub-Saharan Africa, approximately 1.3 million ha are estimated to be under some form of CA practice, involving some 500,000–600,000 smallholder farmers in southern Africa (Kassam et al., 2014; Whitfield et al., 2015). Farmers often partially adopt or disadopt CA practices when donor funding runs out. Some resource-constrained farmers are only willing to try the technology when they receive free inputs, which is not sustainable.

In Malawi, many studies show several factors that affect adoption of CA practices (Ngwira et al., 2014; Holden et al., 2018; Chinseu et al., 2019; TerAvest et al., 2019; Hermans et al., 2020; Jew et al., 2020). A study conducted in the southern part of Malawi shows that a shortage of labor and finance to purchase fertilizer and improved seeds influenced the adoption of CA practices (Jew et al., 2020). Ngwira et al. (2014) also found that the availability of labor, cultivated land area, and group membership affected the adoption of CA practices in central and southern Malawi. The study on the effects of CA practices on labor use and financial returns among smallholder farmers in Nkhotakota and Dowa districts shows that input costs and low output prices constrain the profitability of CA practices (TerAvest et al., 2019). Holden et al. (2018) studied the role of a lead farmer promoter-adopter approach in enhancing adoption of CA and found positive results. Chinseu et al. (2019) found that the main driver of CA disadoption is CA implementation arrangement stating that CA is a labor-saving, time-saving, and yield-improving technology that farmers could not realize.

In Zambia, studies on the uptake and intensity of CA practices show several factors that affect its adoption. For example, a survey on the adoption and adoption intensity of minimum tillage using panel data (2010–2014) collected for crop production forecast found that seasonal rainfall and being in a district where minimum tillage was promoted as impediments (Ngoma et al., 2016). Arslan et al. (2014) studied adoption of minimum soil disturbance and crop rotation using Rural Agricultural Livelihood Survey (RALS) data collected in 2004 and 2008 and found that extension services, rainfall variability, agroecology, and socioeconomic factors affect their adoption. Other studies show that using CA benefits farmers technically by increasing productivity (Abdulai, 2016; Abdulai and Abdulai, 2017) and environmentally by reducing the environmental burden from surplus nitrogen (Abdulai and Abdulai, 2017). In Zimbabwe, CA adoption and its intensity is affected by education, institutional support, and agroecological location (Mazvimavi and Twomlow, 2009; Pedzisa et al., 2015b).

However, previous studies on CA adoption had methodological and data limitations to rigorously identify the drivers and barriers of CA adoption. First, most studies only used quantitative methods and data collected for purposes other than studying CA adoption. For example, in Zambia, crop forecast data (Ngoma et al., 2016) and RALS data (Arslan et al., 2014) were used to study adoption of CA practices. Second, some studies used small samples, which are not nationally representative. For example, Ngwira et al. (2014) used only 151 adopters and 149 nonadopters from 10 extension planning areas in central and southern Malawi districts to study the adoption of CA practices among smallholder farmers in Malawi. Abdulai (2016) also used data collected from 408 households from 12 districts in Central, East, West, and Southern provinces to study the determinants and impacts of CA practices on household welfare. Third, some studies, such as Arslan et al. (2014), used old data (2004–2008) and may fail to inform the prevailing situation about CA adoption. Our study uses representative quantitative and qualitative data collected from various agroecologies to analyze drivers and barriers of CA adoption in southern Africa. More specifically, this study analyzes smallholder farmer contexts and decision-making regarding CA practices to identify barriers to sustainable adoption and inform scaling strategies for wider adoption. The rest of the paper is structured as follows: The next section presents the methodology and approach adopted, whereas the third section presents and discusses study findings. The last section concludes with policy implications and recommendations.

1 CA is a farming method based on (a) minimal mechanical soil disturbance, (b) permanent organic soil cover by crop residues and cover crops, and (c) diversified crop rotations or associations with legumes. As such it removes the components of conventional agricultural systems that lead to soil and land degradation.

2. Materials and methods

2.1. Survey design

This study uses qualitative and quantitative data collected by the International Institute of Tropical Agriculture (IITA) and the International Maize and Wheat Improvement Center (CIMMYT) in 2021 from 27th March to 10th May in Malawi, 25th April to 6th June in Zambia, and 24th March to 30th April in Zimbabwe. In Malawi, we used a multistage sampling approach to select districts, extension planning areas (EPAs), sections, villages, and focus groups for focus group discussions (FGDs); and households for the quantitative interviews. We selected three districts from lowland agroecology and four from the mid-elevation upland plateau. The districts represent the major agroecologies in Malawi and are high in CA prevalence according to National CA Task Force Team and some literature (e.g., Ngwira et al., 2014; TerAvest et al., 2019). We used high CA prevalence as criteria to choose EPAs and sections and random sampling to select villages and households. Finally, our sample in Malawi comprised 1,512 households and 126 focus groups selected from seven districts, 21 EPAs, 63 sections, and 189 villages. We conducted two FGDs per section, one for each women and men.

Similarly, we used the same approaches to select seven districts in Zambia representing three agroecological regions and based on CA prevalence – Choma and Siavonga from Region I; Chipata, Kaoma, and Mumbwa from Region II; and Mpongwe and Serenje from Region III. We selected two blocks per district and two camps per block using high CA prevalence as a criterion. In the subsequent stages, we used random sampling to select two villages per camp and 25 households per village, making the total sample 1,407 households. We conducted 112 focus group discussions (two focus groups – one for women and men – per village). Unlike in Malawi where we conducted FGDs at the selection level, in Zambia, we conducted FGDs at the village level because the number of households in a village in Zambia is equivalent to the number of households in a section in Malawi.

In Zimbabwe, we selected 10 districts representing all five agroecological zones based on high CA prevalence (Table 1). We selected two high CA prevalent wards per district in the second stage. In the subsequent stages, we randomly selected three villages per ward and 25 households per village, with the ultimate sample size of 1,455 households. We conducted two FGDs per ward, culminating in 40 FGDs in total. Table 1 presents the sample households and FGDs in the three countries, and Figure 1 shows the geographical distribution of the households.

TABLE 1 Sample size distribution by district and agro-ecological zone.

Districts	Agro-ecological description	Number of FGs	Number of households
Malawi districts			
Nsanje, Nkhotakota, and Balaka	Low land: 250–760 m asl	54	648
Dowa, Rumphi, Chitipa, and Zomba	Mid-altitude: >761 m asl	72	864
Total		126	1,512
Zambia districts			
Choma and Siavonga	Region I: <800 mm	32	400
Chipata, Kaoma, and Mumbwa	Region II: 800–1,000 mm	48	602
Mpongwe and Serenje	Region III: >1,000 mm	32	405
Total		112	1,407
Zimbabwe districts			
Chiredzi and Matobo	Region V: <500 mm	8	300
Bubi, Zaka, and Masvingo	Region IV: 450–600 mm	12	450
Gokwe South and Kwekwe	Region III: 600–700 mm	8	253
Nyanga, Murehwa, and Shamva	Region II: 700–1,050 mm	12	452
Total		40	1,455

2.2. Data

2.2.1. FGDs and household survey

The content of the FGDs, among others, investigated the extent to which drought, heat, flood, soil fertility decline, soil erosion, and pests and diseases affect crop production in the communities of the focus groups. Using a pairwise ranking approach, the focus groups ranked the factors and discussed what farmers do to minimize the effects the identified factors. They discussed to what extent and how CA helps to reduce these effects. The focus groups also discussed the trends in and reasons for adoption, nonadoption, and dis-adoption of CA practice components – minimum soil disturbance (ripping, planting basins, and zero tillage), mulching, and cereal-legume rotation and intercropping. Besides, they discussed sources of CA information, and their participation in CA promotion activities such as attending field days and hosting demonstration plots. Finally, the focus groups ranked CA components according to farmer preference.

For the household study, we used a structured questionnaire developed by the socioeconomics team, reviewed by CA technical experts, and programmed in the World Bank's Survey Solutions computer-assisted personal interviews (CAPI) software. Among others, the household survey included modules on: (1) demographic characteristics; (2) ownership of land, livestock, and other assets; (3) major agricultural production constraints; (4) access to credit; (5) social capital and networking; and (6) conservation agriculture knowledge and adoption. Before the final data collection, we pre-tested the questionnaire and implemented it with trained enumerators and close supervision and backstopping of the senior staff to ensure quality data collection.

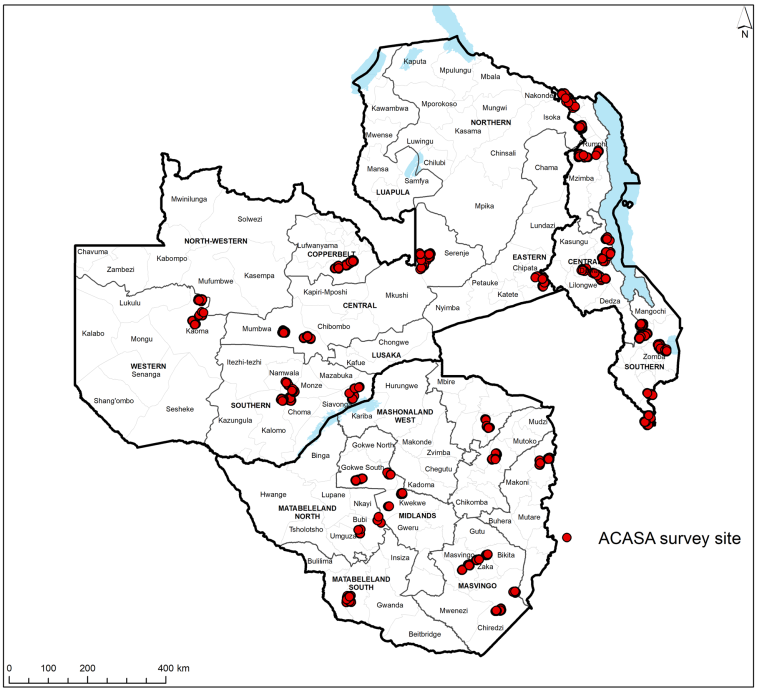

FIGURE 1
Study sites.

2.3. Data analysis

We use descriptive statistics and econometric models to analyze the data. Qualitative data are converted to quantitative data and summarized. The hypothesis and justification of variables in the model are given in Table 2. We used a pairwise ranking approach (Russel, 1997) to rank major constraints to agricultural production and farmers' preferences for CA practices. We also used a multivariate probit model to examine determinants of CA adoption. Below is a detailed description of the multivariate probit model.

2.4. Econometric framework and estimation strategy

2.4.1. Estimating the determinants of CA adoption

A farmer's decision to adopt or abandon a particular agricultural technology or practice is affected by several factors (Foster and Rosenzweig, 2010). These factors include (1) household characteristics such as age, gender, education level, and occupation of the household members who make a decision; household size and marital status; (2) ownership of the farm and non-farm assets, including land and livestock, (3) social capital and networks such as membership to and role in farmers organizations, kinship and other networks, (4) access to extension services, availability and costs of inputs and credit, (5) farmers behavior such as risk attitude and time preference, (6) availability of output markets and reasonable prices, and (7) biophysical factors such as the occurrence of pests and diseases, drought and flood; soil quality, water availability, topography, and seasonal temperature changes, among others. Table 2 summarizes the hypothesized determinants influencing adoption of CA in the study countries. Furthermore, we assume interdependence of adoption decision of CA practices, i.e., adoption decision of one CA component depends on the adoption decision of other CA components. Thus, all CA components have to be modelled simultaneously. This assumption is informed by the fact that CA tends to significantly impact crop yields more when all three CA principles are implemented (TerAvest et al., 2019) and has been promoted as such. Jew et al. (2020) also note that the partial application of CA principles gives a lower yield than full CA. The case at hand calls for a model that can handle all CA components to take care of potential correlations. The Multivariate Probit (MVP) model uses concurrent interdependent equations for adopting different agricultural technologies (Khanna, 2001; Belderbos et al., 2004; Gillespie et al., 2004; Ndiritu et al., 2014). Following Gillespie et al. (2004) and Ndiritu et al. (2014), we can express MVP as two systems of equations.

The first system of the equations is:

$$Y^*_{hj} = \beta'_j x_h + \varepsilon_h, \quad j = MT, M, R, I \tag{1}$$

where Y^*_{hj} is a latent (unobservable) dependent variable representing a level of benefit or utility derived from the adoption of $MT, M, R, and\ I. X_{hp}$ denotes observed characteristics of the household, h. Where MT, M, R, and I stand for minimum tillage, mulching, rotation, and intercropping, respectively. A household adopts CA practices if the benefit from adoption exceeds that from nonadoption.

The second system of equation expresses an observable binary choice of CA practices by households as follows:

TABLE 2 Hypothesized determinants/factors influencing adoption of CA in southern Africa.

Independent variable/factor	Measure	Sign	Justification
Household head age	Years	+	Older farmers with better farm experience are more likely to practice CA (Mazvimavi and Twomlow, 2009; Ngwira et al., 2014; Ng'ombe et al., 2017).
Household head gender	1 = Male, 0 = female	+	Female farmers tend to have labor constraints and may not practice all components of CA (Mazvimavi and Twomlow, 2009; Congress et al., 2010; Ngwira et al., 2014; Ng'ombe et al., 2017).
Household head education level	Years	+	Increases the speed with which CA information is processed and may likely lead to CA adoption (Kotu et al., 2017; Ng'ombe et al., 2017; Khonje et al., 2018).
Household size	Number of family members	+	May reflect labor endowment for a household need to address perform various CA-related application activities (Ngwira et al., 2014).
Kinship	Number of relatives within or outside the village	+	Reflects household's social capital and its power in information sharing regarding CA practices (Fisher et al., 2018).
Farmer group membership	1 = Yes, 0 = no	+	Increases farmer access to key services such as credit and extension critical for CA uptake.
Extension access	Number of extension contacts per agricultural season	+	Extension services increase information on CA awareness and subsequent uptake and application of CA principles (Mazvimavi and Twomlow, 2009; Wossen et al., 2017; Fisher et al., 2018; Ngoma et al., 2021).
Cultivated land	Hectares (ha)	+	Gives the farmer the flexibility to practice CA alongside other conventional practices thereby spreading the risk. However, the expected effect is mixed depending on the type of technology under consideration. (Mazvimavi and Twomlow, 2009; Ngwira et al., 2014; Ngoma et al., 2021).
Share of rented in land	% of rented in land	–	Reflects tenure security status and reduces the likelihood of investing in CA due to the limited time horizon as a result of lack of land tenure security rights. (Arslan et al., 2014).
Access to subsidized inputs	1 = Yes, 0 = no		Provide incentive for farmer to practice CA.
Livestock ownership	Total tropical livestock units (TLU)	–	May conflict with CA principles (such as mulching) uptake due to competition over crop residues for feed. (Ngwira et al., 2014; Ng'ombe et al., 2017).
Own radio	1 = Yes, 0 = no	+	Enhances access to information on CA.
Own mobile phone	1 = Yes, 0 = no	+	Enhances access to information on CA (Wossen et al., 2017).
Own bicycle	1 = Yes, 0 = no	+	Enhances access to information on CA.
Own motorbike	1 = Yes, 0 = no	+	Enhances access to information on CA aiding mobility to extension and input service providers.
Risk aversion	1 = Yes, 0 = no	–	Risk averse farmers are less likely to adopt new technologies like CA as opposed to conventional tillage (Mazvimavi and Twomlow, 2009; Arslan et al., 2014).
Time preference	1 = high discount rate, 0 = low discount rate	–	Farmers who prefer immediate benefits are less likely to adopt CA.
Value of farm assets	(MWK) (ZMK) ($)	+	Reflects wealth status of a household and the ability to finance key inputs (including labor) required for adoption of CA.
Off-farm employment	1 = Yes, 0 = no	+	Offers alternative source of income that may be used to invest in CA technologies such as herbicides and pay labor (Wossen et al., 2017).
Market distance	Km	–	Increases transaction costs and thus limit access to inputs/ technologies (Kotu et al., 2017; Wossen et al., 2017).
District/geographical location	1 = Yes, 0 = no	±	Accounts for agroecological differences that may have mixed effect on adoption of CA (Mazvimavi and Twomlow, 2009; Arslan et al., 2014; Pedzisa et al., 2015a,b; Ng'ombe et al., 2017).

$$T_{hj} = \begin{cases} 1 & if\ Y_{hj}^{*} > 0,\ and \\ 0 & otherwise \end{cases} \quad (2)$$

where T_{hj} is the adoption of the j^{th} CA practice by the h^{th} household.

In this model, we assume the stochastic terms (ε_{MT} , ε_M , ε_R , and ε_I) to be a jointly distributed multivariate normal random variable ($(MVN(0,\varnothing))$, where $\varnothing$ is a variance–covariance matrix given as follows:

$$\varnothing = \begin{bmatrix} 1 & p12 & p13 & p14 \\ p21 & 1 & p23 & p24 \\ p31 & p13 & 1 & p34 \\ p41 & 42 & p43 & 1 \end{bmatrix} \quad (3)$$

The off-diagonal elements represent estimates of the correlations between the equation error terms, $rho(\rho)$, for any two adoption equations in the MVP model. According to Ndiritu et al. (2014), when there is a correlation between the error terms, the off-diagonal elements in the variance–covariance matrix of adoption equations become non-zero, and equation 1 becomes an MVP model. A positive correlation shows a complementary relationship, while a negative correlation shows a substitute relationship among CA adoption decisions. The model was estimated based on the Geweke–Hajivassiliou–Keane (GHK) simulation method and maximum likelihood estimation (Cappellari and Jenkins, 2003).

3. Results and discussion

3.1. Focus group discussion results

3.1.1. Biotic and abiotic constraints to maize production

The results of the FGDs show that drought is the number one constraint to crop production in Zambia and Zimbabwe, while the same is true for pests and diseases in Malawi (Table 3). Soil fertility decline is the other major constraint to crop production in the three countries. Heat is another important constraint in Zimbabwe. In Malawi and Zambia, men and women focus groups ranks are similar.

Table 4 presents measures to minimize the impacts of the three major crop production constraints in Malawi and Zambia. The results of the multiple responses show that mulching can improve declining soil fertility through the supply of organic matter and drought by preserving moisture. In Zambia, conserving water and minimum tillage can minimize the effects of drought and declining soil fertility, respectively. The focus groups also indicated that preserving soil moisture and cereal legume association can help reduce the effects of drought and declining soil fertility in Zambia. Forty percent of men and women focus groups in Malawi and 51% of women focus groups in Zambia think CA cannot address crop production problems caused by pests and diseases.

In contrast, a quarter of men focus groups in Malawi, and about half of men focus groups in Zambia perceive that crop rotation and intercropping can interrupt the lifecycle of some pests and diseases and thus minimize crop damage. The focus groups with a positive impression of CA on pests and diseases argued that crop rotation and intercropping break pest lifecycles, and crop residue mulching hinder the infestation of crops by pests and diseases. Tambo and Kirui (2021) in their study in Zambia also found that conservation agriculture can offset the negative effects of fall army worm infestation on maize yield. However, some farmers view these positive benefits as not being substantial enough. However, 40% of men and 43% of women focus groups in Malawi and 51% of women focus groups in Zambia think CA does not help combat the problem of crop pests and diseases. In Malawi, the focus group said fall armyworm attacks maize on CA and conventional farm fields.

Moreover, crop residue retention encourages termite infestation and pest transfer from the previous growing season. In Malawi, 40% of women's focus groups reported a lack of knowledge on how CA can minimize the effects of pests and diseases. In Malawi and Zambia, the difference in perception of measures to reduce the effects of the constraints is trivial.

In Zimbabwe, men's focus groups indicated that drought and heat affect livestock in all districts; and winter plowing, preparing basins as early as possible, and retaining crop residue are mentioned as the measures to minimize the effects of drought. The third constraint to crop production in Zimbabwe, according to the FGDs, is soil fertility decline. According to the FGDs, using fertilizer, legume-cereal rotations, intercropping, and applying humus, ash, compost, anthill soil, topsoil, and manure can minimize the effects of soil fertility decline.

3.1.2. Preference for conservation agriculture practices

Table 5 presents pairwise ranking results on the preferences of the components of CA practices by focus groups. The focus groups ranked the components of the CA practices based on their experiences and perceived benefits from using the CA practices or the benefits they have observed from their neighbors. Results indicate that Full CA is the most preferred practice by men and women focus groups in Malawi and Zambia and women focus groups in Zimbabwe. In Zimbabwe, men's focus groups ranked minimum tillage and cereal-legume rotation/intercropping first and the full CA third. The main reason for ranking full CA as first was the maximum yield benefits associated with its use compared to other options. In Malawi and Zambia, focus groups perceive cereal-legume rotation/intercropping as a crop diversification strategy that hedges against crop failure, mainly maize, the dominant food crop in the three countries.

3.1.3. Barriers to the adoption of conservation agriculture

Figure 2 presents the results of the FGDs on barriers to CA adoption in the communities. In Malawi, the main barriers to adopting CA practices are lack of interest and incentive and labor intensive nature of the CA practices. Limited technical knowledge about CA application, burning of crop residue by mice hunters,

TABLE 3 Pairwise ranking results of agricultural production constraints.

Constraints	Malawi			Zambia			Zimbabwe
	Men	Women	Total	Men	Women	Total	Total
Pests and diseases	1	1	1	2	2	2	4
Drought	3	3	3	1	1	1	1
Soil fertility decline	2	2	2	3	3	3	3
Soil erosion	4	4	4	4	5	5	5
Heat	5	6	5	4	4	4	2
Floods	6	5	6	6	6	6	5
Number of focus groups	63	63	126	57	55	112	40

pests and disease, competition for crop residues for livestock feed and tobacco nurseries, and limited access to farm inputs also affect adoption of CA practices. In Zambia, the main barriers to adopting CA practices are labor intensity, limited access to farm inputs, limited technical knowledge about CA application, lack of interest and incentive, and weed infestation. In Zambia, ripping is the dominant practice that needs capital to purchase rippers and herbicides. Limited technical knowledge about CA application also hindered CA adoption in Zambia. The results align with the findings of the study in southern Africa (Lee and Gambiza, 2022). In Zimbabwe, The labor-intensive nature of CA practices is the main barrier to its adoption.

3.2. Household survey results

3.2.1. Characteristics of the sample households

Table 6 presents descriptive results of the characteristics of minimum tillage (MT)-based CA adopters and nonadopters. MT-based CA adopters are those farmers who adopted minimum tillage for at least two consecutive years, including the 2020/21 farming season. The results show that, in all countries, CA adopters have a higher education level and are also members of farmer organizations and risk-takers than nonadopters. Higher education could help adopters obtain, process, and utilize information relevant to CA practices better than nonadopters. In Malawi and Zambia, adopters of CA practices have more household members, number of relatives within or outside the village (kinship), and extension contacts per year. Kinship shows a household's social capital, and the results signal the power of social capital in information sharing regarding CA practices. Besides, in Malawi, more CA adopters than nonadopters own radios and bicycles, have more access to non-farm employment, are wealthier (livestock and land), and have a lower discount rate. In Zambia, more adopters than nonadopters own radios, phones, bicycles, and motorbikes; have access to non-farm employment and subsidized inputs such as fertilizer, improved seed, and herbicides; are wealthier (livestock and land); and have a lower discount rate. In Zimbabwe, more CA adopters than nonadopters own phones and motorbikes; and have access to subsidized inputs such as fertilizer, improved seed, and herbicides. Ownership of phones, motorbikes, and bicycles has a bearing on access to information, including CA practices and a low discount rate, meaning they are willing to give up something beneficial today to benefit more in the future. Adopters have more access to subsidized inputs such as fertilizer, improved seed, and herbicides than nonadopters in Zambia and Zimbabwe presence of organizations promoting CA practices. Therefore, wealthier and more educated farmers with more land and livestock are more likely to adopt CA practices, which are capital- and knowledge-intensive.

3.2.2. Biotic and abiotic constraints to maize production

Figure 3 presents major abiotic and biotic constraints to maize production in Malawi, Zambia, and Zimbabwe. The results show declining soil fertility in Zambia (62% of households) and Malawi (59% of households) and drought in Zimbabwe (52% of households) are the major maize production constraints among smallholder farmers. Declining soil fertility is also one of the constraints to maize production in Zimbabwe.

3.2.3. Awareness of conservation agriculture practices

Awareness[2] of CA practices is a precursor to adoption. Figure 4 presents farmers' awareness of CA practices in the three countries. The results show a high level of awareness (above 70%) of minimum tillage, mulching, and rotation among smallholder farmers in all three countries. The awareness of intercropping and crop rotation in Zimbabwe is relatively low. The highest awareness of intercropping in Malawi could be due to the small landholding size. The high awareness of minimum tillage and crop residue mulching in the three countries could be attributed to large-scale investments in CA characterized by CA promotion efforts by various stakeholders, including governments, NGOs, and the private sector.

Table 7 presents the proportion of households trained in CA practices and the adoption rates among the trained ones. The results show that training on CA practice is the highest in Zimbabwe (93%), followed by Zambia (87%). The results also show that the adoption of CA practices is higher among the trained households. Malawi and Zambia follow the training of trainers approach. In this approach, extension workers train lead farmers to train fellow farmers, usually

2 In this study, awareness of CA is defined as "having heard about CA practices" while "knowledge of CA" refers to "having technical knowledge to apply CA to crop fields."

TABLE 4 Perception on how CA addresses crop production constraints by gender (% of focus groups).

	Malawi		Zambia	
	Men	women	Men	women
Drought				
CA preserves/conserves soil moisture or water	93.6	93.6	100	100
CA is not applicable	3.2	4.8		
Do not know if CA can address drought	3.2	1.6		
Declining soil fertility				
Mulch adds to organic matter, which improves soil fertility	98.4	96.7	7.1	14.6
Minimum tillage improves manure/ fertilizer-use efficiency			66.1	56.4
Cereal-legume rotation/intercropping improves soil fertility			25.0	12.7
Others measure but not CA			1.8	10.9
CA cannot at all address declining soil fertility		3.3		5.5
Do not know if CA can address declining soil fertility	1.6			
Pests and diseases				
Crop rotation and intercropping interrupt the lifecycle of crop-specific pests and diseases (1 = yes)	25.4	6.4	48.2	20.8
Mulching reduces pest infestation (e.g., FAW)	12.7	9.5		
CA is less effective in addressing the problems of pests and diseases	6.4	1.6		
CA encourages early planting, which allows crops to mature before pest infestation			8.9	1.8
CA promotes a good plant population which makes it easy to spot pests and diseases			5.4	5.4
Moisture preserved in planting basins reduces pest infestation			1.8	1.8
CA cannot at all address pests and diseases	39.7	42.9	23.2	50.9
CA is not applicable to address pests and diseases			1.8	
Do not know if CA can address pests and diseases	15.9	39.7	7.1	17.0

organized in farmer groups. However, the training of trainers approach may not work well as claimed by the promoters because CA is knowledge-intensive, and lead farmers may not be able to understand and transfer knowledge to other fellow farmers. For example, discussions with extension workers in Malawi's selected extension planning areas (EPAs) revealed knowledge gaps. Farmers complained of receiving message about of conflicting messages about CA practices like the mulch promotes pest infestation, e.g., fall armyworm. Thus, there is a need to train extension workers on CA and harmonize CA extension messages among stakeholders to avoid

TABLE 5 Pairwise ranking of the preferences of CA practices by country and gender of the focus group.

CA practice	Malawi		Zambia		Zimbabwe	
	Men	Women	Men	Women	Men	women
Full CA	1	1	1	1	3	1
Minimum tillage and cereal-legume rotation/ intercropping	2	2	2	2	1	2
Minimum tillage and residue mulching	3	3	3	3	2	2

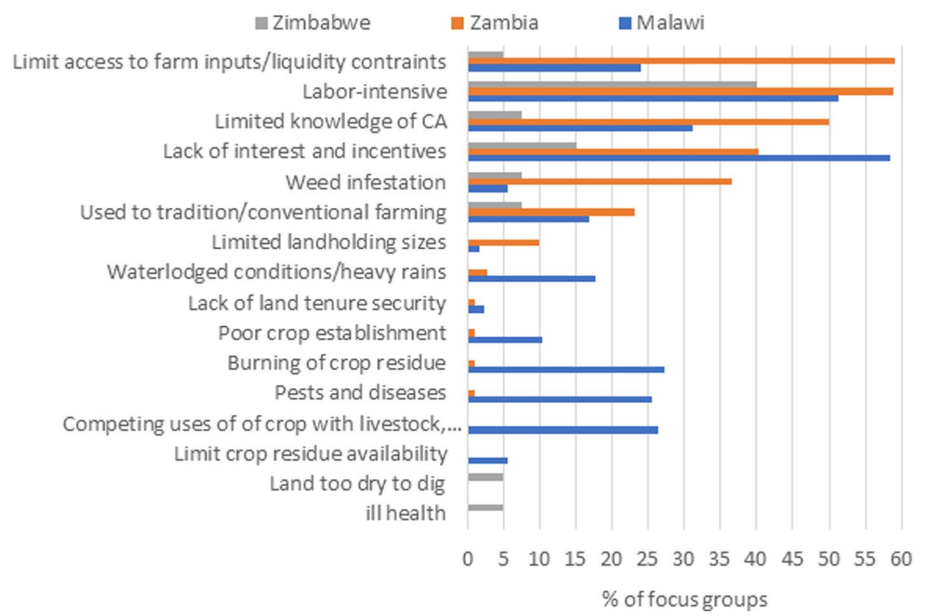

FIGURE 2
Farmers perceptions about barriers to CA adoption (% of focus groups).

conflicting CA messages, revisiting the lead farmer concept through regular training and reference manuals in vernacular or local languages.

Because CA is knowledge-intensive, learning by doing, such as hosting demonstration plots, is very important. The results show that a few households hosted demonstration plots. For instance, among the sample households aware of minimum tillage, only 7% in Malawi, 14% in Zambia, and 24% in Zimbabwe hosted demonstration plots (Table 8). However, most farmers who hosted the demonstration plots applied the same CA practice on their non-CA demonstration plots implying that CA demonstration plots are important in equipping smallholder farmers with the technical skills to implement CA. Demonstration plots are also helping fellow farmers within and neighboring communities to learn about CA practices.

3.2.4. Adoption and disadoption of conservation agriculture practices

Table 9 presents estimates of adoption rates of the CA components and subcomponents by country. The results show that the adoption of minimum tillage, the main[3] CA component, is highest in Zambia, followed by Zimbabwe, probably because of actively run CA projects. Malawi has the least adoption rate of minimum tillage (only 4%). Similarly, Zambia has the highest adoption rate of mulching, followed by Zimbabwe. Adoption rates of cereal-legume rotation, an old-age traditional practice, are high in all three countries. Malawi exhibited the highest adoption rate for intercropping possible because of land shortage. Adoption of intercropping is low in Zambia and Zimbabwe, where the landholding size is relatively large. Zambia exhibited the

3 We consider minimum tillage as the main component of CA as it is the foundation for applying the remain two components or principles. Besides, literature such as (Ngoma et al., 2021) and other donors consider minimum tillage as the main CA component. This is so because CA focuses on reduced soil disturbance where tillage is done only in planting stations and the rest of the soil is left undisturbed. Ngoma et al. (2021) note that MT is the most prevalent and nonnegotiable CA component.

TABLE 6 Household characteristics by minimum tillage-based adopters and non-adopters (mean).

Variables	Malawi			Zambia			Zimbabwe		
	Adopters	Nonadopters	*p*-values	Adopters	Nonadopters	*p*-values	Adopters	Nonadopters	*p*-values
Household head age	48.63	45.65		49.43	47.06	***	55.63	53.13	***
Household head gender (1 = female)	0.11	0.23	**	0.23	0.23		0.34	0.35	
Education level of the household head (years)	7.73	6.21	***	6.88	6.01	***	7.92	7.57	*
Household size	5.71	5.18	**	6.49	5.86	***	5.54	5.42	
Kinship	4.08	3.48		6.46	5.60	**	8.46	7.98	
Farmer group membership	0.50	0.35	**	0.83	0.68	***	0.60	0.50	***
Extension contacts	2.73	1.79	***	2.57	1.71	***	7.05	7.15	
Cultivated land (ha)	1.28	0.89	***	2.99	2.25	***	1.76	1.67	
Share of rented in land (1 = yes)	0.17	0.03		0.04	0.06	**	0.01	0.01	
Access to subsidized inputs (1 = yes)	0.89	0.83		0.71	0.51	***	0.95	0.88	***
Livestock ownership (TLU)	1.28	0.60	***	2.88	2.91		3.69	3.89	
Own radio (1 = yes)	0.48	0.35	**	0.63	0.48	***	0.52	0.50	
Own mobile phone (1 = Yes)	0.81	0.62		0.91	0.81	***	0.95	0.91	***
Own bicycle (1 = yes)	0.48	0.39	***	0.73	0.51	***	0.33	0.29	
Own motorbike	0.07	0.04		0.04	0.02	**	0.0	0.02	***
Risk aversion (1 = yes)	0.27	0.45	***	0.52	0.60	***	0.37	0.43	**
Time preference (1 = Yes high discount rate)	0.24	0.41	***	0.49	0.60	***	0.47	0.47	
Value of farm assets (MWK)	105,000	97,176							
Value of farm assets (ZMK)				530,000	14,349				

(Continued)

TABLE 6 (Continued)

Variables	Malawi			Zambia			Zimbabwe		
	Adopters	Nonadopters	*p*-values	Adopters	Nonadopters	*p*-values	Adopters	Nonadopters	*p*-values
Value of farm assets ($)							980.49	1319.77	
Off-farm employment	0.63	0.44	***	0.22	0.19		0.36	0.26	***
Market distance (Km)	189.54	193.77		160.96	145.39	***	105.69	115.22	***
Nsanje	0.19	0.14							
Nkhotakota	0.08	0.15							
Balaka	0.23	0.14	*						
Dowa	0.11	0.15							
Rumphi	0.19	0.14							
Chitipa	0.10	0.14							
Zomba	0.10	0.15							
Choma				0.10	0.19	***			
Siavonga				0.04	0.26	***			
Kaoma				0.17	0.12	**			
Mumbwa				0.23	0.05	***			
Mpongwe				0.16	0.13				
Serenje				0.19	0.10	***			
Chipata				0.13	0.16	*			
Bubi							0.08	0.12	***
Chiredzi							0.05	0.14	***
Gokwe South							0.16	0.06	***
Kwekwe							0.06	0.08	*
Masvingo							0.19	0.04	***
Matobo							0.11	0.09	
Murewa							0.13	0.08	***
Nyanga							0.06	0.14	***
Shamva							0.06	0.14	***
Zaka							0.10	0.10	
N	62	1,450		747	660		638	817	

*$p < 0.10$.
**$p < 0.05$.
***$p < 0.01$.

highest adoption rate (33%) of full CA, followed by Zimbabwe (21%). Malawi has the least adoption rate of Full CA (2%). The high adoption rates of CA practice in Zambia and Zimbabwe are mainly because the studies were conducted in areas with reportedly higher past CA investments (Mazvimavi and Twomlow, 2009). A study in Zambia also shows that our sample districts are among those that received active CA support from donors. Zimbabwe has a relatively more extended CA promotion history than Zambia and Malawi.

An assessment of adoption of the various CA subcomponent practices shows that planting basins are the main minimum tillage practice in all countries. Most households reported adopting planting basins in Zimbabwe (91%) and Malawi (90%). Planting basins and ripping are equally important in Zambia (64 and 62%).[4]

4 This may be attributed to relatively high prevalence of Magoye ripper in Zambia (Arslan et al., 2014; Tambo and Kirui, 2021). A Magoye ripper is a farm mechanization machinery that is used to open up planting furrows leaving the soil of the other part of the field undisturbed. It is usually ox-drawn in Zambia.

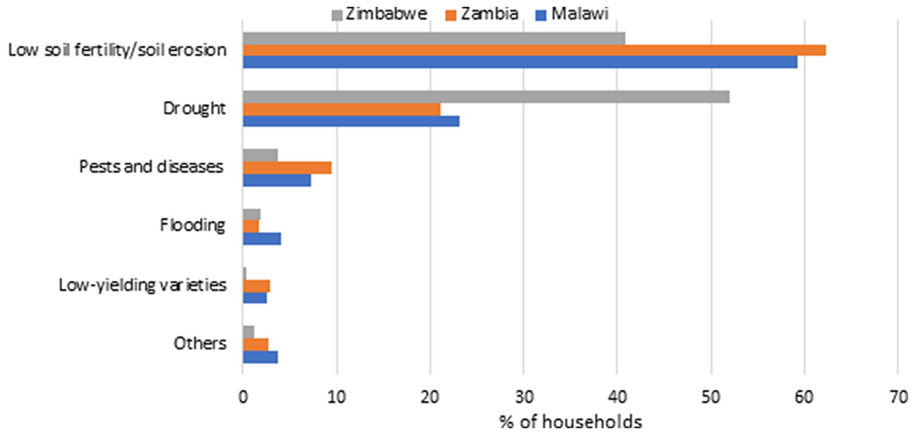

FIGURE 3
Major constraints to maize production disaggregated by country (% households).

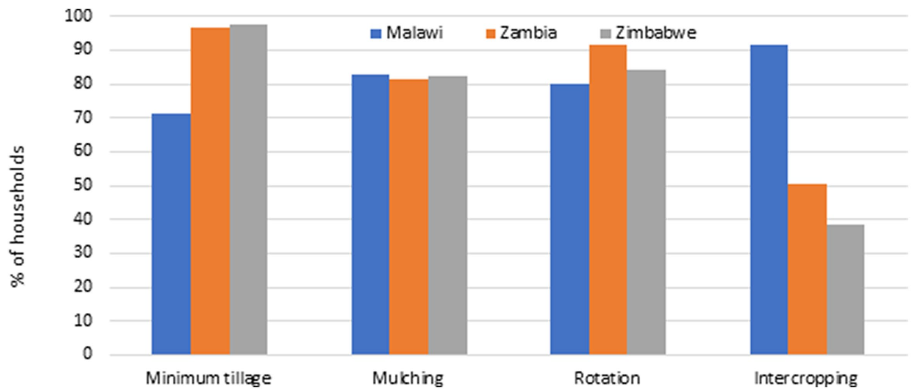

FIGURE 4
Awareness of CA practices by country (% of households).

From mulching subcomponents, maize residue mulching is common in Zambia (97%) and Malawi (88%). Farmers also adopt grass residue mulching in Zimbabwe (58%) and Zambia (49%). Results also show that Zambia has diversified mulching materials, including groundnut residues (33%) and soybean residues (27%). Diversification of mulching material is important because most smallholder maize plots hardly produce enough maize crop residues to cover at least 30% of their fields, the standard level to qualify as mulching. The typical crop rotation practice for all three countries is cereal-groundnut rotation, with over 68% of the households, and the common intercropped legumes are common beans, groundnut, and soybeans.

A comparison of awareness and adoption rates of CA practices (Figure 5) shows a wide gap between awareness and adoption for all CA practices. The gaps are wider for minimum tillage and crop residue mulching in Malawi, suggesting that much of the awareness of CA practices has not translated to adoption. Thus, there is a need for alternative and practical extension models in bridging the knowledge gap regarding CA practices in these countries.

Disadoption of CA practices is one of the challenges facing CA promotion efforts. Table 10 presents dis-adoption rates of CA practices by country. Malawi showed high dis-adoption rates for minimum tillage (60%) and mulching (58%). For all CA practices, the disadoption rates are low in Zimbabwe (less than 10%) and about a quarter in Zambia. The observed dis-adoption rates for crop rotation and intercropping are low as these are traditional practices. A qualitative assessment of farmers' perceptions about the reasons for the dis-adoption of CA practices in Malawi shows the labor-intensive nature associated w+ith CA practices (35%), pests and diseases infestation (25%), and unavailability of crop residues (20%) as familiar major drivers to CA dis-adoption.

3.2.5. Perception of conservation agriculture practices

Farmers' perception of new agricultural technologies is important in their decision to adopt (Mekonnen et al., 2018). Identifying misperceptions in new agricultural technologies is vital in determining

It is used to addresses the drudgery associated with minimum tillage-based practices. The furrows improve water infiltration and harvest water that will be made available to the plant.

TABLE 7 Training and adoption of CA practices.

CA practices	Malawi				Zambia				Zimbabwe			
	Number aware	% Trained	% Adopted among trained	% Adopted among non-trained	Number aware	% Trained	% Adopted among trained	% Adopted among non-trained	Number aware	% Trained	% Adopted among trained	% Adopted among non-trained
MT	1,078	46.5	9.4	2.6	1,357	87.3	59.4	24.2	1,419	93.4	46.0	29.8
Mulching	1,252	46.6	18.0	2.4	1,145	82.0	67.3	24.3	1,201	91.8	34.2	14.1
Rotation	1,213	31.5	70.9	55.0	1,287	79.4	85.2	76.2	1,226	80.8	81.5	73.8
Intercropping	1,385	19.7	68.5	63.3	711	56.4	40.9	20.0	558	62.4	57.5	29.5

how extension programs reduce knowledge gaps. Figure 6 presents households' perceptions of new agricultural technologies in Malawi, Zambia, and Zimbabwe.

Results show that more than 80% of the households in Zambia and Zimbabwe and 68% in Malawi update themselves with current information on farming practices. Moreover, in all three countries, farming households perceive traditional practices as inferior and are willing to change their farming practices. However, over 65% of farmers are cautious in trying the new practices, and nearly 80% of the households in Malawi and Zimbabwe try out only promising practices. Besides, 58% of the households check out for favorable results from their neighbors' fields before trying them out. These results call for the establishment of demonstration plots near farmers' farm fields. Besides, there is a need for vibrant extension networks that work to showcase agricultural technologies in practice and enable farmers to evaluate the benefits of these technologies for increased CA adoption. Dalton et al. (2014) found similar results, i.e., farmers require tangible evidence before adopting technologies, and peer evidence is a vital source of information. As presented in 3.2.3 above, CA is knowledge-intensive, and demonstration plots provide the farmers a platform to learn by doing, where extension workers impart technical skills on CA application to farmers. Besides, most farmers who hosted the demonstration plots applied the same CA practice on their non-CA demonstration plots implying that CA demonstration plots are important in equipping smallholder farmers with the technical skills to implement CA.

3.2.6. Farmer assessment of the importance of technical, social, institutional, and economic factors in nonadoption and dis-adoption of CA practices

Figure 7 presents reasons for nonadoption and dis-adoption of CA practices among households that did not adopt or dis-adopted CA practices. Despite the high awareness of CA practices, more than 50% of nonadopter or dis-adopter households in Zimbabwe and around 70% of the households in Malawi and Zambia mentioned limited technical knowledge of CA practices as the main reason for nonadoption and dis-adoption of CA practices in all the countries. This could be because the CA promotion models widely used in the three countries – the lead farmers approach – is limited in transferring knowledge needed to practice CA. According to Friedrich et al. (2009), CA is a complex and management-intensive farming concept in which crop management must be planned proactively and not reactive, as in the standard tillage-based systems. Finance is another limiting factor for adoption of CA among smallholder farmers in all three countries. Thirty-one percent of the households in Zimbabwe, 48% in Malawi, and 72% in Zambia have indicated unavailability of credit to finance the purchase of inputs as a reason for nonadoption or disadoption of CA practices. Other reasons for disadoption of CA practices are poor access to extension, high cost of fertilizer, unavailability of legume seeds for intercropping/rotation, high labor costs at the time of planting, drudgery, unavailability of compatible herbicides, and weeds. Because CA does not provide immediate benefits and requires additional inputs, there is a need to support smallholder farmers, especially in the initial years, through different mechanisms to promote adoption of CA. Households also mentioned the limited availability of crop residues because of free grazing and uncontrolled wildfires suggesting a need for local-level institutional bylaws to protect crop residues from free grazing and fire.

TABLE 8 Hosted demonstration of CA practices and applied the practice in non-demo plots (% of households).

CA practices	Malawi			Zambia			Zimbabwe		
	Number aware	% Hosted	% Applied	Number aware	% Hosted	% Applied	Number aware	% Hosted	% Applied
Minimum tillage	1,078	6.68	58.3	1,357	13.8	98.4	1,419	24.0	96.2
Mulching	1,252	8.39	60.0	1,145	8.9	92.2	1,201	18.9	94.7
Rotation	1,213	1.73	76.2	1,287	4.5	94.8	1,226	13.4	96.6
Intercropping	1,385	0.72	90.0	711	3.2	87.0	558	10.2	96.5

3.2.7. Determinants of adoption of CA practice

Table 11 shows the likelihood ratio test results of the null hypothesis of independent error terms of the four equations (minimum tillage, mulching, intercropping, and crop rotation) that rejects $\left(p > chi^2 = 0.00\right)$ the hypothesis. The pairwise correlations between the coefficients of the error terms are significant for all pairs in Zambia and Zimbabwe and 67% of pairs in Malawi. These results imply that the probability of adopting one of the CA practices is not independent of the decision to adopt other CA practices and thus justifies our choice of the MVP model instead of the univariate probit model. The positive sign of the coefficients shows the complementarity of the CA components. This assumption was informed by the fact that CA components are complementary. The qualitative assessment also indicated that farmers prefer a combination of CA components, particularly full CA, due to the maximum yield benefits of full CA instead of using a single CA component. Positive correlations also proved the assumption among the error terms for various CA components (equations).

Table 12 presents the results of the MVP model for the four CA practices in the three countries. The results show that the gender of the household head positively and significantly influenced crop rotation and intercropping adoption in Malawi and mulching in Zimbabwe. The implication is that female household heads are more likely to adopt crop rotation, intercropping, and mulching in the two countries. The adoption of intercropping could be related to female preferences for producing diverse crops for home consumption (Croppenstedt et al., 2013) or a function of their socially assigned roles as food crop producers. More specifically, female farmers are more involved in producing legumes as food and nutrition security crops, while male farmers grow cash crops such as tobacco. On the other hand, the positive effect of gender on the adoption of mulching may be influenced by the fact that mulching is relatively less labor-intensive as it eliminates the need for weeding. Thus, female farmers are more likely attracted to it than minimum tillage, which is considered more labor-intensive.

The age of the household head has positively and significantly influenced crop rotation adoption in Malawi and Zimbabwe, intercropping in Malawi and Zambia, and minimum tillage and mulching in Zimbabwe. The results align with previous studies (Ngoma et al., 2021). Ngoma et al. (2021) noted that CA elements such as rotations and intercropping are old-age practices prevalent in conventional farming. Older farmers are more likely to adopt these than young farmers. The significant effect of the age of the household on the adoption of minimum and mulching in Zimbabwe may be due to a relatively long history of CA promotion relative to the two countries. The household head's education also influences the adoption of crop rotation in Malawi and Zimbabwe, minimum tillage and intercropping in Malawi, and mulching in Zambia and Zimbabwe. The findings also agree with the results by (Khonje et al., 2018), who found a positive effect of education on adopting multiple agricultural technologies in Eastern Zambia. Education level increases the capacity and speed of processing CA information (Kotu et al., 2017). The higher the education level, the greater the awareness and subsequent change in attitude and practice. Because CA is complex and knowledge-intensive, it requires more careful planning than standard tillage (Congress et al., 2010).

The size of total cultivated land influenced the adoption of minimum tillage in Malawi and Zimbabwe; mulching in Malawi, crop rotation in Malawi, Zambia, and Zimbabwe; and intercropping in Zimbabwe. These results align with the study conducted in Eastern and Southern Africa (Ngoma et al., 2021). Ngoma et al. (2021) note that larger landholding sizes allow farmers to experiment with CA on some parts of their land while maintaining the low-risk and low-return conventional farming methods. Livestock ownership measured as total livestock units (TLU) has a negative and statistically significant coefficient for mulching in Zambia, indicating that households who own more livestock, especially cattle (free grazers), are less likely to adopt mulching. The fact that livestock competes for crop residues in the form of feed contributes to limited crop residues left for mulching—a lack of supportive institutional bylaws regarding free grazing and wildfires in the study areas.

The value of farm assets has a statistically significant effect on adopting all four CA practices in Zambia and all practices except minimum tillage in Zimbabwe. The value of farm assets reflects the importance of the wealth of households and implies that wealthier households are more likely to adopt CA practices. Dalton et al. (2014) observe limited economic incentives contributing to the limited adoption of conservation practices globally. Access to subsidized inputs influences the adoption of minimum tillage (Zambia and Zimbabwe), mulching (all three countries), and intercropping in Zimbabwe, implying that households with access to subsidized inputs like fertilizer, seeds, and herbicides are more likely to adopt these CA practices. The limited access to farm inputs caused by liquidity constraints was among the major drivers of CA nonadoption and disadoption, according to the focus groups in Malawi and Zambia. Limited access to inputs is one of the technical factors limiting the adoption of CA practices such as minimum tillage and mulching (Friedrich et al., 2009).

Access to extension measured by the number of extension contacts per season positively and significantly influences adopting all CA practices except minimum tillage in Malawi and all the practices except intercropping in Zambia. This implies that households with more extension contacts per season are more likely to adopt mulching. We suggest that the insignificant effect of extension contact on

TABLE 9 Adoption of CA practices by country (multiple responses within a component in % of households).

Minimum tillage	Malawi (*n*=62)	Zambia (*n*=747)	Zimbabwe (*n*=638)
Minimum tillage adoption (%)	4.1	53.1	43.9
Minimum tillage sub-practices			
• Planting basins	90.2	64.4	90.6
• Ripping	1.6	62.0	3.3
• Direct seeding with a dibble stick	8.2	0.9	5.0
• Direct seeding with jab plant		0.27	0.9
• Animal traction direct seeding		0.5	0.2
• Ox-ripping direct seeding		7.6	
Mulching	Malawi (*n* =121)	Zambia (*n* = 682)	Zimbabwe (*n* = 391)
Mulching adoption (%)	8.0	48.5	26.9
Mulching sub-practices			
• Maize residue mulching	88.4	96.8	37.9
• Grass residue mulching	6.6	48.5	57.8
• Soybean residue mulching		27.1	0.8
• Groundnuts residue mulching	3.3	32.7	0.3
• Sorghum residue mulching		4.6	1.0
• Banana leaves residue mulching		1.2	
• Other crops residue mulching	1.7	8.1	2.3
Rotation	Malawi (*n* =727)	Zambia (*n* =1073)	Zimbabwe (*n* =981)
Rotation adoption (%)	48.2	76.3	67.4
Rotation sub-practices			
• Cereal-beans	3.30	54.1	10.3
• Cereal-soybeans	8.70		3.7
• Cereal-cowpea	2.10	10.2	3.7
• Cereal-groundnut	75.7	73.2	68.5
• Cereal-pigeon peas	10.30		
• Cereal-other legumes		22.09	13.8
Intercropping	Malawi (*n* = 890)	Zambia (*n* = 226)	Zimbabwe (*n* = 260)
Intercropping adoption	58.9	16.1	18.1
Intercropping sub-practices			
• Cereal-beans	28.40	54.0	25.8
• Cereal-soybeans	13.30	41.2	4.6

(Continued)

TABLE 9 (Continued)

Minimum tillage	Malawi (n=62)	Zambia (n=747)	Zimbabwe (n=638)
• Cereal-cowpea			
• Cereal-groundnut	7.10	49.1	31.9
• Cereal-pigeon peas	51.2		
• Cereal-other legumes		26.6	37.7
Minimum tillage + mulching adoption	1.9	7.7	7.2
Full CA adoption	1.8	32.8	20.9

N represents number of adopters.

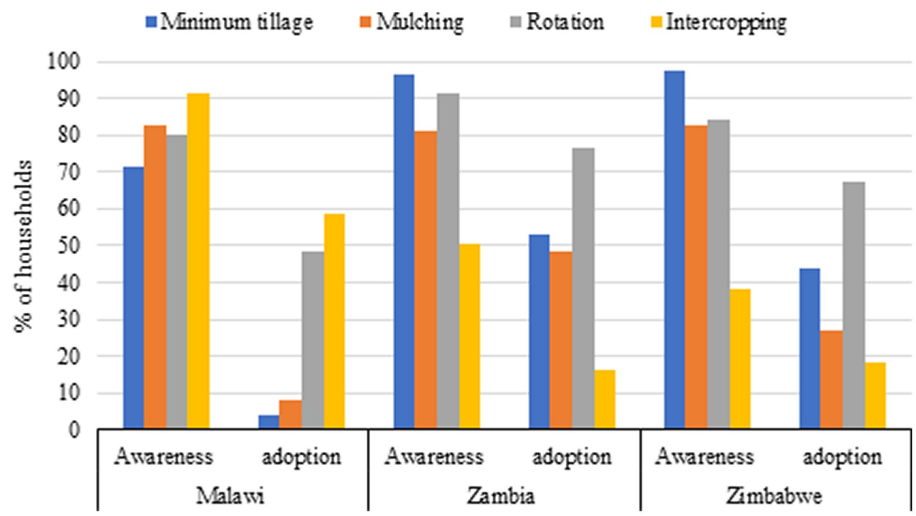

FIGURE 5
Awareness and adoption of CA practices by country and CA practices (% of households).

TABLE 10 Dis-adoption of CA components by country (percent of households).

CA practices	Malawi		Zambia		Zimbabwe	
	Number of ever used	% Dis-adopted	Number of ever used	% Dis-adopted	Number of ever used	% Dis-adopted
Minimum tillage	268	60.1	1,053	18.8	1,300	2.8
Mulching	408	58.1	875	13.7	903	7.1
Rotation	874	11.4	1,181	5.8	1,117	1.6
Intercropping	1,116	14.0	345	23.5	374	8.0

minimum tillage may be explained by the quality of extension advice (technical details) rendered to farmers regarding the proper application of minimum tillage principles. Key informant interviews with some of the extension workers in Malawi revealed knowledge deficiencies about correct CA applications. This finding agrees with findings from FGD, where farmers cited limited access to extension as one of the major factors constraining the Adoption of CA practices.

The study also investigated the effect of other farmer characteristics/attributes that may affect CA adoption, such as attitude toward risk. Risk aversion was negatively and significantly correlated with adopting MT in Zimbabwe, mulching in Malawi, Zambia, and Zimbabwe, and intercropping in Zimbabwe. This suggests that risk-averse farmers are less likely to adopt CA practices. This finding confirms the results on farmer perceptions of CA practices where the majority of the farmers

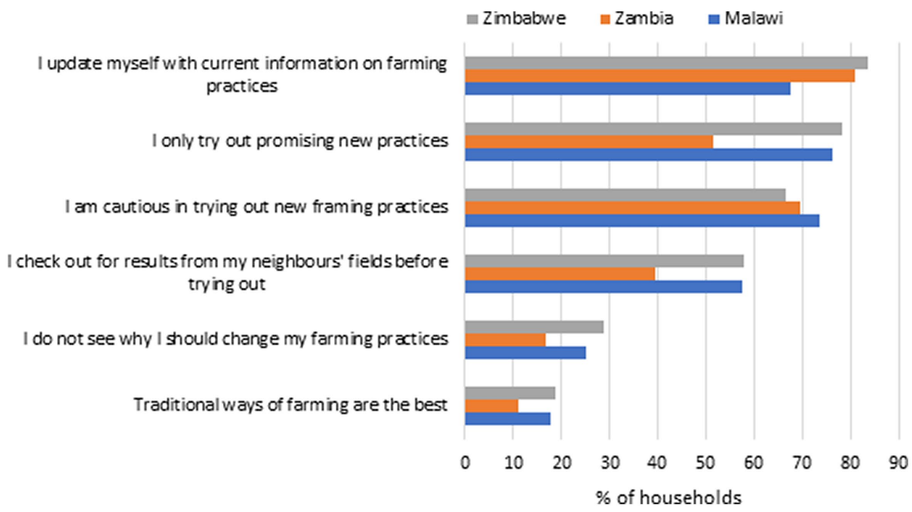

FIGURE 6
Perception of new agricultural technologies by country (% of households).

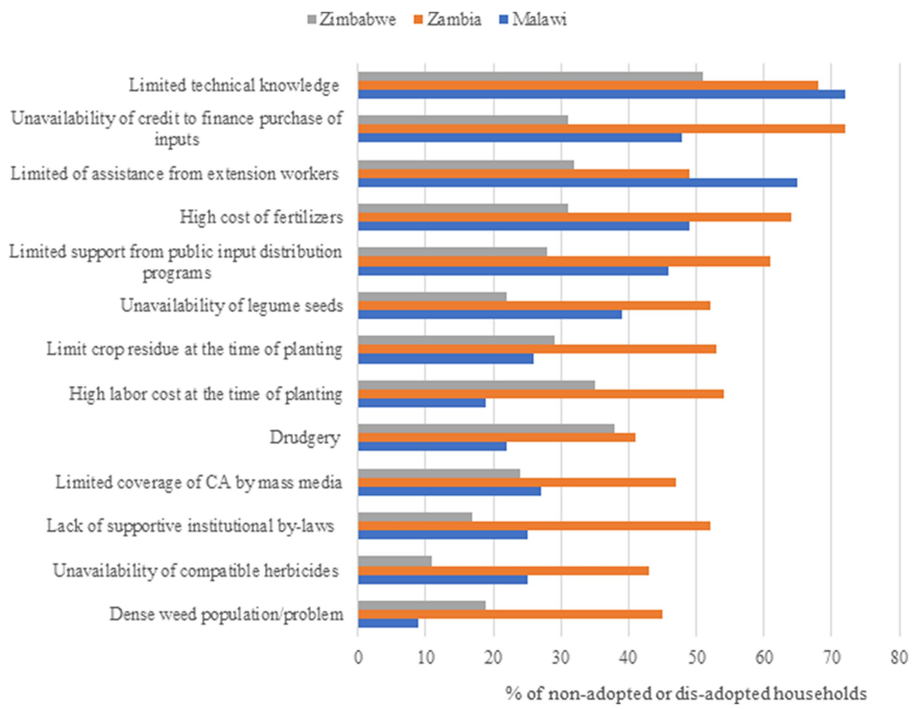

FIGURE 7
The reasons for non-adoption and dis-adoption of CA practices.

(nearly 80%) in Malawi and Zimbabwe only try out promising practices, and 58% of farmers from these countries check out for results from their neighbors' fields before trying out the new agricultural techniques.

4. Conclusions and implications

This study aimed to understand the drivers and barriers to adopting CA practices using data from 278 focus groups and 4,374 smallholders in Malawi, Zambia, and Zimbabwe. The FGDs and the household surveys show that the main constraints to crop production are declining soil fertility, drought/heat, and pests and diseases in the three countries. From the results of the focus groups, using CA practices such as crop residue retention, minimum tillage, crop rotation, and intercropping could reduce the effects of declining soil fertility and drought through conserving moisture, biofertilization, and changing soil properties. However, most focus groups, mostly women, perceive that using CA practices does not help reduce the effects of pests and diseases.

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TABLE 11 Correlation coefficients of error terms obtained from multivariate probit model estimation.

Binary correlation	Malawi			Zambia			Zimbabwe		
	Correlation coefficient	Standard error	Significance level	Correlation coefficient	Standard error	Significance level	Correlation coefficient	Standard error	Significance level
rho21: Mulching and minimum tillage	0.377	0.066	***	0.382	0.039	***	0.638	0.033	***
rho31: Rotation and minimum tillage	0.130	0.059	**	0.381	0.044	***	0.276	0.041	***
rho41: Intercropping and minimum tillage	0.069	0.061		0.122	0.051	**	0.254	0.046	***
rho32: Rotation and mulching	0.100	0.052	*	0.271	0.049	***	0.402	0.042	***
rho42: Intercropping and mulching	0.010	0.055		0.126	0.051	**	0.361	0.046	***
rho43: Intercropping and rotation	0.175	0.042	***	0.273	0.055	***	0.419	0.043	***

Likelihood ratio test of rho21 = rho31 = rho41 = rho32 = rho42 = rho43 = 0: $chi^2(6) = 177{,}639$ Prob > $chi^2 = 0.0000$ where rho1 = minimum tillage; rho2 = crop residue mulching; rho3 = cereal-legume rotation; rho4 = cereal-legume intercropping.
*$p < 0.10$.
**$p < 0.05$.
***$p < 0.01$.

The assessment of awareness of and preference for CA practices shows very high awareness of CA practices but generally low adoption, as observed by several studies in the literature. The gaps are much more significant between awareness and adoption, and much smaller between hosting demonstrations and adoption. The results suggest that much of the awareness of CA practices has not translated to greater adoption, pointing to the need for more technical knowledge regarding CA application rather than mere CA awareness. CA training and demos are better conduits to enhance adoption than awareness creation per se. Hosting demonstrations enhanced adoption of CA as most households that hosted the demonstrations also applied the same on their non-demonstration plots. This suggests that demonstrating the applications and benefits of CA practices is critical for promoting the adoption of CA practices in all countries.

Men and women focus groups in Malawi and Zambia, and women focus groups in Zimbabwe prefer full CA. The justification by the focus groups for selecting full CA is its ability to increase crop yields. In Zimbabwe, men focus groups chose a combination of minimum tillage and cereal legume rotation or intercropping because the use of legumes hedges against crop failure, especially maize. However, adoption of CA practices is low even in CA-prevalent districts in three countries, especially Malawi. In Malawi, the major reasons for farmers not to adopt or dis-adopt CA practices, according to sample households, are limited technical knowledge and limited assistance from extension workers, followed by the unavailability and high costs of inputs. However, focus groups show that the main barriers to adopting CA practices are lack of interest/incentive and labor intensity, limited technical knowledge, and crop residue-related problems.

In Zambia, lack of credit to purchase inputs, limited technical knowledge, high fertilizer cost, high labor cost during planting, and unavailability of legume seeds are among the reasons for not adopting or disadopting CA practices. According to focus groups in Zambia, farmers do not adopt or dis-adopt CA practice mainly because of limited access to inputs and labor intensity, followed by limited technical knowledge and labor intensity. In Zimbabwe, limited technical knowledge is the major factor for not adopting or dis-adopting CA practices, followed by labor intensity according to the sample households; and labor intensity according to focus groups. Limited technical knowledge, limited access to credit, poor access to extension, high cost of fertilizers, unavailability of legume seeds for intercropping/rotation, high costs of labor at the time of planting, drudgery, unavailability of compatible herbicides, and increased weed pressure at the early stage of CA adoption are the main reasons for nonadoption and dis-adoption of CA practices in the three countries.

The adoption rates of CA components and full CA is highest in Zambia and Zimbabwe for most CA practices. The high adoption rates of CA practices in Zambia and Zimbabwe are due to high past and present investments in CA promotion in the study areas. In Zambia and Zimbabwe, the dis-adoption rates are less than the adoption rates for all CA practices. However, in Malawi, the dis-adoption rates are greater than the adoption rates for minimum tillage and mulching.

The results of multivariate Probit (MVP) regression analyses for the four CA practices show that female farmers are more likely to adopt crop rotation and intercropping in Malawi and mulching in Zimbabwe. The age of the household head positively and significantly influenced crop rotation adoption in Malawi and Zimbabwe, intercropping in Malawi and Zambia, and minimum tillage and mulching in Zimbabwe. The education level of the household head

TABLE 12 Determinants of Adoption of CA practices: results of multivariate probit model estimation by country.

Variable	Malawi				Zambia				Zimbabwe			
	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping
Gender of household head (1 = female)	−0.295	−0.116	0.234**	0.211**	0.132	−0.073	−0.041	−0.006	−0.010	0.160*	0.022	−0.046
	(0.20)	(0.15)	(0.09)	(0.09)	(0.10)	(0.09)	(0.11)	(0.11)	(0.08)	(0.08)	(0.08)	(0.09)
Age of household head (years)	0.007	0.006	0.004*	0.008***	0.003	0.001	0.004	0.006**	0.010***	0.011***	0.008***	0.001
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Education level of household head (years of schooling)	0.040*	0.003	0.033***	0.049***	0.018	0.024**	0.017	0.016	0.019	0.040***	0.023*	−0.017
	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Household size	0.005	−0.054*	0.004	0.010	0.017	0.007	0.049**	0.010	0.001	−0.013	−0.014	−0.018
	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Total size cultivated land (ha)	0.199**	0.244***	0.279***	0.080	0.018	0.004	0.040*	0.009	0.066**	0.042	0.052*	0.110***
	(0.08)	(0.07)	(0.07)	(0.06)	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)
Share of rented in land	−0.000	−0.087	0.043	0.001	−0.308	−0.120	−0.469**	−0.175	0.248	−0.287	−0.264	0.118
	(0.00)	(0.21)	(0.14)	(0.01)	(0.21)	(0.20)	(0.21)	(0.27)	(0.43)	(0.41)	(0.46)	(0.47)
Livestock ownership (TTLU	0.028	−0.020	−0.009	0.011	−0.003	−0.014*	−0.004	0.009	−0.012	−0.008	−0.004	−0.012
	(0.03)	(0.03)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)

(Continued)

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TABLE 12 (Continued)

Variable	Malawi				Zambia				Zimbabwe			
	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping
Log of value of farm asset (MK)	−0.016	−0.038	0.047	−0.002	0.104***	0.078**	0.140***	0.094**	0.044	0.121***	0.098***	0.011
	(0.07)	(0.06)	(0.04)	(0.04)	(0.04)	(0.03)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
Off farm employment (1 = yes)	0.218	0.280**	−0.026	−0.024	−0.044	−0.087	−0.179*	−0.215**	0.237***	0.162**	0.153*	0.178**
	(0.15)	(0.12)	(0.08)	(0.08)	(0.09)	(0.09)	(0.10)	(0.11)	(0.08)	(0.08)	(0.08)	(0.09)
Access to subsidized inputs	0.231	0.436**	0.145	0.140	0.223***	0.406***	0.021	0.123	0.436***	0.352**	0.451***	0.569***
	(0.20)	(0.18)	(0.10)	(0.10)	(0.08)	(0.08)	(0.09)	(0.09)	(0.13)	(0.15)	(0.13)	(0.18)
Kinship (number of relatives you can rely on)	0.011	0.017	0.009	0.010	0.011*	0.008	0.016**	−0.001	0.001	0.000	−0.005	−0.000
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)
Access to extension (extension contacts)	0.023	0.062***	0.028**	0.027**	0.037**	0.030**	0.064***	0.011	−0.001	−0.005	−0.000	0.001
	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)
Own radio (1 = yes)	−0.084	0.086	0.031	0.056	−0.006	0.008	−0.137	−0.050	−0.096	−0.162**	0.080	0.054
	(0.15)	(0.12)	(0.09)	(0.09)	(0.09)	(0.08)	(0.10)	(0.10)	(0.08)	(0.08)	(0.08)	(0.09)
Own cell phone (1 = yes)	0.261	0.343**	0.058	−0.079	0.156	0.087	0.135	−0.017	0.206	0.219	0.179	0.442**
	(0.17)	(0.14)	(0.09)	(0.09)	(0.12)	(0.12)	(0.12)	(0.14)	(0.15)	(0.16)	(0.14)	(0.20)

(Continued)

TABLE 12 (Continued)

Variable	Malawi				Zambia				Zimbabwe			
	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping
Own bicycle/ motorbike (1 = yes)	−0.153	−0.018	−0.037	−0.074	0.101	−0.082	0.092	0.031	0.037	0.026	0.181**	−0.085
	(0.17)	(0.14)	(0.10)	(0.10)	(0.09)	(0.09)	(0.10)	(0.11)	(0.09)	(0.09)	(0.09)	(0.10)
Risk aversion (1 = yes)	−0.015	−0.315*	0.162	−0.122	−0.007	0.204**	−0.257**	0.142	−0.188**	−0.251***	−0.067	−0.272***
	(0.21)	(0.18)	(0.11)	(0.11)	(0.10)	(0.10)	(0.12)	(0.12)	(0.09)	(0.09)	(0.09)	(0.10)
Time preference (1 = yes)	−0.184	0.048	−0.117	−0.033	−0.168*	−0.336***	0.241**	0.021	−0.011	−0.066	−0.043	−0.171*
	(0.22)	(0.18)	(0.12)	(0.12)	(0.10)	(0.10)	(0.11)	(0.12)	(0.09)	(0.09)	(0.09)	(0.10)
Market distance to major cities (km)	0.002	0.002*	0.001	−0.004***	−0.004	0.000	0.010***	−0.000	−0.000	0.001	−0.003	0.004
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Balaka	0.302	0.567**	0.467***	0.116								
	(0.26)	(0.24)	(0.14)	(0.14)								
Chitipa	−0.728	−0.302	1.017***	0.533*								
	(0.52)	(0.43)	(0.29)	(0.29)								
Dowa	0.087	0.601**	1.212***	−0.671***								
	(0.27)	(0.25)	(0.14)	(0.14)								
Nkhotakota	−0.382	0.185	0.751***	−1.059***								
	(0.36)	(0.30)	(0.19)	(0.19)								
Rumphi	−0.014	0.483**	1.059***	−0.853***								
	(0.25)	(0.24)	(0.14)	(0.14)								
Nsanje	0.189	0.671**	0.399*	0.551**								
	(0.36)	(0.32)	(0.21)	(0.22)								

(Continued)

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TABLE 12 (Continued)

Variable	Malawi				Zambia				Zimbabwe			
	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping
Mpongwe					0.354*	0.004	−1.368***	−0.255				
					(0.20)	(0.19)	(0.23)	(0.22)				
Serenje					0.851**	0.161	−1.879***	−0.352				
					(0.38)	(0.35)	(0.46)	(0.40)				
Kaoma					1.602*	0.763	−4.171***	0.371				
					(0.94)	(0.85)	(1.13)	(0.98)				
Mumbwa					1.408***	0.741**	−0.790*	0.046				
					(0.35)	(0.31)	(0.40)	(0.35)				
Siavonga					−0.354	−0.340	−2.040***	−0.183				
					(0.26)	(0.25)	(0.31)	(0.29)				
Choma					0.258	0.186	−1.958***	−0.216				
					(0.47)	(0.43)	(0.56)	(0.50)				
Bubi									−1.251***	−0.532**	−0.296	−0.304
									(0.20)	(0.21)	(0.21)	(0.22)
Chiredzi									−1.698***	−0.796*	−0.481	−1.488***
									(0.43)	(0.43)	(0.45)	(0.48)
Kwekwe									−1.158**	−0.919*	−0.351	−1.404**
									(0.51)	(0.54)	(0.54)	(0.57)
Gokwe_ South									−0.285	0.175	0.952*	−0.764
									(0.50)	(0.51)	(0.55)	(0.57)
Matobo									−0.876***	−0.504*	−0.379	−0.210
									(0.26)	(0.27)	(0.27)	(0.28)
Murewa									−0.653***	−0.158	−0.439**	−0.811***
									(0.17)	(0.17)	(0.18)	(0.20)
Nyanga									−1.446***	−0.533*	−0.209	−0.540*
									(0.28)	(0.28)	(0.30)	(0.31)
Shamva									−1.404***	−0.465**	−0.403*	−1.090***
									(0.23)	(0.23)	(0.23)	(0.26)

(Continued)

TABLE 12 (Continued)

Variable	Malawi				Zambia				Zimbabwe			
	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping	Minimum tillage	Mulching	Rotation	Intercropping
Zaka									−0.972***	−0.837***	−1.007***	−0.179
									(0.16)	(0.17)	(0.17)	(0.17)
_cons	−3.071***	−2.902***	−2.357***	0.417	−1.571***	−1.426***	−1.094***	−2.315***	−0.722**	−2.324***	−0.759**	−1.622***
	(0.76)	(0.61)	(0.40)	(0.39)	(0.31)	(0.30)	(0.34)	(0.34)	(0.36)	(0.38)	(0.36)	(0.41)
N	1,505				1,405					1,449		

Standard errors in parentheses.
Log pseudo likelihood = −2336.1928.
Wald $chi^2(96) = 654.88$***.
*$p < 0.10$.
**$p < 0.05$.
***$p < 0.01$.

positively influenced adoption of minimum tillage, rotation, and intercropping in Malawi, mulching in Zambia, and mulching and rotation in Zimbabwe. Total cultivated land size significantly influenced the adoption of minimum tillage, mulching, and crop rotation in Malawi; only rotation in Zambia; minimum tillage and rotation/intercropping in Zimbabwe.

The findings generally suggest an affordable supply of physical and financial inputs and the establishment of demonstration plots near farmer fields. More specifically, there is a need for investments in a dense network of highly visible and accessible community learning centers and vibrant extension networks for CA. Besides, most of the current investments in CA promotion are short-term, and there is a need for long-term on-farm demonstrations to enable farmers to understand and appreciate the benefits of CA. There is also a need to develop integrated weed management systems adapted to smallholder farming conditions. Thus, our study contributes to the recommendation in literature (e.g., Mafongoya et al., 2016) about the need to profile the technology, the farmers' socioeconomic circumstances, and the bio-physical environment in which the farmer operates for proper agroecological and beneficiary targeting to achieve more significant impact at scale.

Data availability statement

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

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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EDITED BY
Pankaj Kumar Arora,
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India

REVIEWED BY
Folorunso Mathew Akinseye,
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Kenya
Samuel Orisajo,
Cocoa Research Institute of Nigeria (CRIN),
Nigeria

*CORRESPONDENCE
Olubukola Oluranti Babalola
✉ olubukola.babalola@nwu.ac.za

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Agroecological techniques: adoption of safe and sustainable agricultural practices among the smallholder farmers in Africa

Akinlolu Olalekan Akanmu[1], Anne Margaret Akol[2], Dennis Obonyo Ndolo[3], Funso Raphael Kutu[4] and Olubukola Oluranti Babalola[1]*

[1]Food Security and Safety Focus Area, Faculty of Natural and Agricultural Sciences, North-West University, Mmabatho, South Africa, [2]Department of Zoology, Entomology and Fisheries Sciences, College of Natural Sciences, Makerere University, Kampala, Uganda, [3]Biopesticides Group, International Centre for Genetic Engineering and Biotechnology (ICGEB), Cape Town Component, Cape Town, South Africa, [4]School of Agricultural Sciences, Faculty of Agriculture and Natural Sciences, Mbombela, South Africa

Attaining sufficiency in food supply to support a growing population without compromising ecosystem functioning remains a top agenda of researchers and agricultural stakeholders. Agroecological farming approaches are effective techniques that ensure sustainable food production even in adverse situations. Population growth has been forecasted to reach over 9.1 billion by 2050 outpacing food production. However, cereals and grain legumes are strategic to achieving the United Nations Sustainable Development Goal of zero hunger by 2030 (SDG 2), ending extreme poverty (SDG 1), and mitigating the climate change effect (SDG 13). There remains an urgent need to embrace more sustainable measures to increase food production for the growing population. This review explores the role of agroecology which employs a transdisciplinary approach to sustainable agricultural practices to improve the resilience of farming systems by increasing diversification through poly-cropping, agroforestry, use of local varieties, and integrated crop and livestock systems. Furthermore, the agroecological farming approach minimizes water use, lowers pollution levels on the farm, and ensures economic profitability for the farmers. Thus, application of agroecology techniques among the smallholder farmers is strategic to ensuring food security.

KEYWORDS

agroecological farming, sustainable development goals, sustainable food production, small-scale farmers, economic profitability

Introduction

The United Nation's second Sustainable Development Goal (SDGs-2) aims to "end hunger, achieve food security and better nutrition," and promote sustainable agriculture by 2030 (Lartey, 2015). However, the current state of global agricultural and food systems does not guarantee adequate nutrition and food security. There are currently around a billion hungry people globally, which is forecasted to double as the global population reaches 9.1 billion by 2050 (Tripathi et al., 2019; Ikrang et al., 2022). Although over 60% of the population depends on agriculture for food and income, the current population growth rate has outpaced food production (Porkka et al., 2017; Odusola, 2021). Contemporary agricultural practices are characterized by expansive monocultures, the use of high-yielding crop varieties, synthetic fertilizers and agrochemicals including pesticides, fuel-based mechanization, and extensive irrigation operations. Although these practices are able to increase yields, they have failed to eliminate hunger and thereby raise serious concerns regarding the economic, social, and environmental sustainability of the modern farming practices. Industrial agriculture also produces between 25 and 30% of the world's greenhouse gas (GHG) emissions, further aggravating the effects of climate change and jeopardizing the ability of the planet to provide sufficient and nutritious food into the future (Liu et al., 2020).

The current annual usage of pesticides stands at over 2.6 million tons with a market value of more than US$ 25 billion (Rajbhandari, 2017; Abd-Aziz et al., 2022). Such massive use of pesticides often impairs natural regulating systems and contributes towards the loss of biodiversity that would otherwise support food production. The use of high-yielding crop varieties and synthetic fertilizers appears to offer only short-term benefits and have failed to stem declining yields, especially among major cereal and legume production regions (Rajbhandari, 2017; Kuyah et al., 2021). Meanwhile, the current rate of global population's growth has outpaced that of food production, hence, resulting in severe food shortages, chronic hunger and malnutrition especially among the least developed regions of the world (Smith and Glauber, 2020). Many African nations are currently in this category. Despite agriculture being considered as the backbone of the economy and its significant contribution to the livelihood of majority in Africa, most nations in the continent are still challenged by factors which hinders agricultural productivities such as declining soil fertility, climate change effects, water shortages, post-harvest losses, and restricted market access among others (Gashu et al., 2019). This condition has presently resulted in food security challenges, as recently reported in Ethiopia (Yigezu Wendimu, 2021), South Africa (Chakona and Shackleton, 2018), Nigeria (Ayinde et al., 2020), Ghana (Atanga and Tankpa, 2021), Rwanda (Chigbu et al., 2019), and Cameroon (Mbuli et al., 2021) among many others. Hence, the need for a new paradigm for agricultural growth that supports more environmentally friendly, biologically diversified, long-lasting, resilient, and socially acceptable agricultural practices.

The foundation for these new agricultural systems comprise at least 75% of the 1.5 billion smallholder composed largely of family farmers and indigenous people operating 350 million small farms that occupies about 20% of the world's arable land and providing no less than 50% of the world's agricultural production for home consumption (Machovina et al., 2015). Agroecology which has been increasingly recognized for its potential to bring about the transformative changes necessary to meet the SDGs is one such holistic and people-centered farming approach that embraces a long-term vision and has the potential to help successful transitions towards sustainable agriculture and food systems (Anderson et al., 2019a). Agroecology is an applied science that employs ecological concepts and principles to build and manage sustainable agroecosystems with minimal reliance on external inputs but more on natural processes like biological control and natural soil fertility without expanding the agricultural land base (Hathaway, 2016). This ecology-based discipline is characterized by five principles: diversity, efficiency, natural regulation, synergies, and recycling (Anderson et al., 2019a). Agroecological transitions toward more sustainable agriculture and food systems have been categorized into three major categories namely; increasing eco-efficiency, input substitution, and system redesign (Landert et al., 2020).

Agricultural intensification: applications of sustainability in diverse settings

The need for sustainable agriculture came to the limelight in the early 1980s in response to a variety of ecological concerns However, since sustainable agriculture is a normative notion, different fields and affiliations have given it diverse meanings (Mohd Hanafiah et al., 2020). However, the traditional view of sustainable agriculture frequently concentrates on contexts of on-farm and watershed-level sustainability of agriculture with an emphasis on ecological and agronomic dimensions (Martin et al., 2018). Although the commonly practiced conventional approach of agriculture which entails utilization of non-organic fertilizer and pesticides has made considerable strides, but has disregarded some crucial contextual features such as the culture, food tradition, human and social values, and only partially able to identify some broad trends in sustainable agriculture. Since the 1950s, industrialization, and uniformity in the production, transportation, and sale of food and fiber have caused the agricultural systems to become more and more defined by monocultural landscapes. There has therefore been an increase in the consolidation of small farms and the tendency toward economies of scale (Petersen-Rockney et al., 2021). Conventional agriculture in industrialized nations has been negatively linked to excessive energy use, the loss of small farms, and local biodiversity within its framework of massive, heavily financed, automated farms and expanding food networks (Gomiero et al., 2008). These unfavorable consequences have had a significant impact on how the idea of sustainable agriculture has emerged in industrialized nations. In these nations, attempts to reorganize the environmental, sociocultural, geographical, and temporal components of the traditional food system serve as the foundation for ideological concepts of sustainable agriculture (Eakin et al., 2017). This reframes the link between agriculture and the environment by utilizing techniques like organic and biodynamic farming (Muhie, 2023). The nature of the geographical and temporal exchanges that occur in traditional agriculture has also changed as a result of the use of alternative food channels that connect customers and producers directly, such as farmers' markets and community-supported agriculture.

In contrast to industrialized nations, efforts towards sustainable agriculture in poor nations place a greater emphasis on the economic independence, health, and cultural lives of producers than on the esthetics or environmental advantages to the consumers. Agroecological management-based crop and animal diversification reduces the economic risk and uncertainty associated with pest and disease outbreaks and declining prices of agricultural produce (Garrett et al., 2020). Therefore, an integrated farming system with diverse forms of production is characterized by the integration and recycling of various on-farm components to enhance the economic benefits and self-sufficiency in resource utilization (Garrett et al., 2020; Hercher-Pasteur et al., 2021). The intricacies of resource use in sustainable agricultural initiatives in poor nations differ from those in developed countries. Movements for sustainable agriculture in developing nations have emerged as an immediate response to the national economic crises by thriving toward a self-sufficient economy (Lang

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and Barling, 2012). Therefore, the practices of agroecology have been embraced as approaches that offer resilience for restructuring agricultural development, in spite of the variation in the practice of sustainable agriculture and food security from country to country. The report of Wezel et al. (2014) enumerated a total of 15 the agroecological practices, 9 of which was considered as poorly integrated in agriculture such as the applications of natural pesticides, biofertilizers, crop rotations and crop choice, agroforestry with fruit, nut trees or timber, intercropping and relay intercropping, mulching or direct seeding into living cover crops and integration of semi natural landscape elements at field and farm. However, the agroecological practices that are already well integrated include reduced tillage, organic fertilization, split fertilization, cultivar choice and biological pest control.

Adoption of agroecological techniques among the smallholder farmers: the impact on food sovereignty

Small-scale agriculture has, in recent times, received more global attention. This is a result of the realization of its immense potential contribution to solving food security problem even in the face of energy, economic and climate change challenges (Simon et al., 2020). More so, agroecology principles support the plight of the small-scale farmers for food sovereignty. According to La *Via* Campesina, "Food Sovereignty is the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems" (Huambachano, 2019). In essence, food sovereignty describes how food security could be attained. Thus, the concepts of food sovereignty and agroecological-based production systems have received a lot of attention globally over the past 20 years, due to their prospects of increasing food production and bettering the lives of the poorest. Therefore, if the most effective agricultural methods are to be employed, a radical change toward agroecology must be embraced (Peredo Parada et al., 2020) because ecologically based management strategies in agroecosystems and agricultural landscapes can increase the sustainability of agricultural production while reducing off-site consequences Matson et al. (1997).

Agroecology is one of the most reliable routes of attaining sustainable development in the face of the current and expected future climatic, energy, and economic conditions (Streimikis and Baležentis, 2020). Currently, the global "agrarian revolution" is receiving its scientific, methodological, and technical foundation from agroecology (Kohler and Negrão, 2018). Hence, the agroecology-based production system is the foundation of the food sovereignty approach because they are resilient, efficient, biodiverse, and socially acceptable (Anderson et al., 2019b). It is a system that is characterized by a vast diversity of domesticated plant and animal species that are maintained and improved to ensure the appropriate biodiversity, soil conservation, and water regime management that are supported by intricate traditional knowledge systems (Marchetti et al., 2020). These systems have nourished a vast majority of the population for generations. The practice of small-scale farming employs the principles of recycling, diversity, synergy, and integration as well as social processes that value community involvement and empowerment, is the major means of promoting an agroecological development paradigm set to meet the world's food needs in this era of increasing oil cost and climate change coupled with the socioecological importance of peasant agriculture (Wezel et al., 2020).

The agroecological features of smallholder farming systems have demonstrated an efficient farming techniques without depending on the aid of chemical fertilizers, pesticides, mechanization, or other modern agricultural science technologies (Altieri et al., 2012). Traditional farmers in many developing nations have created complex farming techniques that have been passed down from generation to generation. A successful indigenous agricultural strategy is shown by the continued use of more than 3 million hectares of traditional agriculture in the form of terraces, raised fields, agroforestry systems, and polycultures, among others (Koohafkan and Altieri, 2011). Thus, the majority of traditional agroecosystems share some outstanding characteristics, which entail a stable agroecosystem that is resilient, minimizes the risk of losses, and adapts to adverse conditions caused by human or natural events. The traditional practices as well produce a variety of products that support both food and livelihood security (Quiroz-Guerrero et al., 2020). More so, these systems are supported by farmers' inventions, technology, and traditional knowledge, which results in high levels of biodiversity that are essential for controlling the ecosystem function and for delivering important ecosystem services from local to global levels (Singh M., 2021). The traditional agroecosystems are characterized by innovative landscapes, water and land resource management, and conservation technologies that enhance ecosystem management. Also, socio-cultural practices, such as ingrained institutions for agroecological management, normative agreements for resource access and benefit sharing, value systems, etc., are governed by strong cultural values (Marchi et al., 2018; Tittonell, 2020).

Agricultural systems are dynamic and influenced by population growth, scientific and technological advancements, global market forces, agricultural subsidies, consumer demands, climatic change and variability, and pressure from social movements calling for land reform, food sovereignty, and poverty reduction (Harmanny and Malek, 2019). Agroecologists have therefore redesigned and optimized smallholders' agricultural systems using agroecological concepts and techniques in order to make them more responsive to these factors and potentially viable in a world that is changing rapidly (Barrios et al., 2020). The majority of what could be considered the pillars of sustainable management of agricultural systems are shared by most of the agroecological-based systems that have been successful in terms of productivity and resilience (Sandhu, 2021). These entail (i) raising the production efficiency of all farms, (ii) improving the resilience and ensuring risk reduction, (iii) enhancing biodiversity, ecological services, and resource conservation (iv) supporting social justice, cultural diversity, and economic prosperity, (v) increasing reliance on renewable resources while improving natural cycles, and (vi) preventing damage to the environment and to the land. Agroecological systems obviously place strong emphasis on promoting food sovereignty, which advocates for the right and access of everyone to food that is safe, nourishing, and culturally appropriate for food in sufficient quantity and quality to supports a healthy life while maintaining human dignity. In furtherance of this, the agroecological plan also aims at improving energy and technical sovereignty in light of the anticipated rise in the cost of fuel and inputs (Ramankutty and Dowlatabadi, 2021).

We therefore hypothesize that re-designing of the food systems through agroecological techniques entails consideration of the contributory roles of the biotic and abiotic influences on the ecological services and agroecosystem functions. Mores so, the farmers planned agroecological techniques which aims at attaining improved soil quality and plant health, higher productivity, enhanced socio-ecological resilience, autonomy and food sovereignty are further shaped by innovative approaches and social movements. Thus, achieving these requires an enabling environment for agroecological practices that could be derived through responsible governance. More so, agroecological production and consumption are facilitated by the context and innovative approaches that modulates the social and institutional improvements while the practice of circular and solidarity economy prioritizes the promotion and development of local economies by promoting solutions based on the local needs, resources, and the capabilities to build a fairer and sustainable markets that empowers the smallholders' farmers (Figure 1).

Agroecology and sustainable agricultural practices: the African perspectives

Smallholder farmers reportedly feed about one-third of the 238 million people who live in towns and cities, and the majority of the 712 million hungry people who live in rural and remote areas across the world (Altieri et al., 2012). This implies that small-scale farming supports about half of the world's population, and produces at least 70% of the world's food, this on plots averaging 2 ha (Kihara et al., 2020; Sheppard et al., 2020). More so, millions of smallholders and their family, and indigenous people are engaged in resource-conserving farming, a practice that has greatly contributed to food security and improvement of agricultural systems despite the unfavorable climatic and environmental conditions in many areas (Powlson et al., 2011). The traditional agricultural practices that are still operational in many countries throughout Asia, Latin America, and Africa make up an important and inventive agricultural heritage that reflects the value of the diversity of agricultural practices adapted to different environments. This makes up a significant neolithic heritage, although modern agriculture continuously jeopardizes the viability of this legacy (Koohafkan and Altieri, 2011). More than 1.9 million plant types have been reportedly submitted to the world's gene banks by indigenous farmers and peasants, who have created 5,000 domesticated crop species (Kinfe and Tesfaye, 2018). Also, rather than use commercial hybrid seeds, majority of smallholders cultivate their crops using self-bred seeds. Farmers are protected by such genetic diversity from pests, diseases, droughts, and other pressures as the population of diverse and adaptable landraces, as well as weedy and wild relatives of crops, can be found in traditional agroecosystems (Mercer et al., 2019). They are also able to make use of the whole spectrum of agroecosystems that exist in each location and vary in terms of altitude, slope, water availability, soil quality, etc (Quiroz et al., 2018). The stability of agricultural systems is increased by genetic diversity, which also enables farmers to take advantage of various microclimates and employ genetic variation across species for a variety of nutritional and other purposes (Nonić and Šijačić-Nikolić, 2021; Singh R. P., 2021).

According to recent studies, many smallholder farmers adapt to and even prepare for climate change by using more drought-tolerant local varieties, water collecting techniques, agroforestry, mixed cropping, soil conservation measures, and a variety of other age-old methods to reduce crop failure (Nyang'au et al., 2021). Small-scale farms constitute the majority of farms and farm produce, especially in rural Asia and Africa. For instance, only a few of the farmers cultivate more than 2 hectares of rice out of over 200 million rice farmers that reside throughout Asia, and the majority of the rice produced by Asian small-scale farmers is made up of local cultivars, which are often cultivated in highland environments or under rain-fed circumstances (Altieri et al., 2012). About half of the global small-scale farms are practiced on 193 million ha in China, followed 93 million in India representing 23% of global small-scale farms, then Indonesia, Bangladesh, and Vietnam (Shams et al., 2020). In

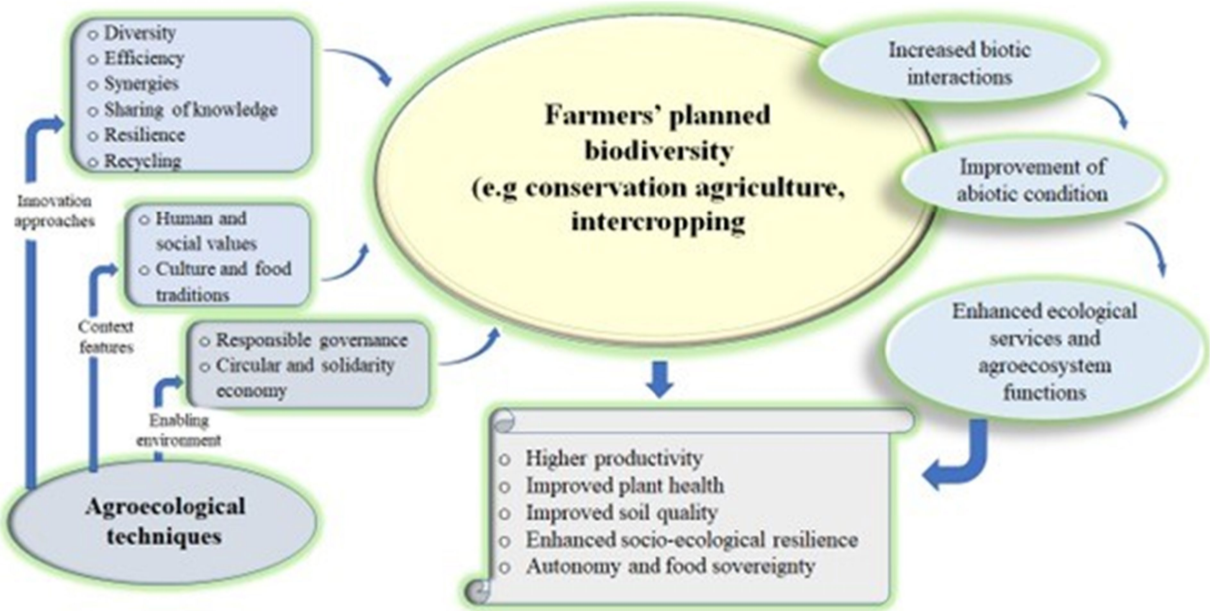

FIGURE 1
The agroecological features of smallholder farming systems.

China alone, there are about 75 million rice farmers who continue to employ techniques dated back to more than a thousand years (Altieri and Nicholls, 2017). In Latin America, smallholder's production units employ 16 million peasant farmers who produce 51 percent of the region's maize, 77 percent of its beans, and 61 percent of its potatoes while providing about 41% of the agricultural output for domestic consumption (McMichael and Schneider, 2011). In Brazil, about 4.8 million family farmers who comprise about 85% of the entire country's farming community work on 30% of Brazil's total agricultural land (Cabral et al., 2016). Similarly, the National Program for Local Innovation in Cuba has successfully spread agroecological innovations that have been shown to improve food security and food sovereignty while coping with and reducing the negative impact of climate change (Fernandez et al., 2018).

Africa presents a peculiar situation as regards the adoption of agroecological practices among the small-scale farmers. A number of farmers, mostly women, were of the opinion that the agroecological models place further pressure on the small-scale farmers by their need to prepare organically acceptable farm additives such as composts, biochar and biopesticides by themselves (Mestmacher and Braun, 2021). More so, the assurance of obtaining better performance as in the case of disease management compared to the conventional farming technique is not guaranteed. Some, therefore, opined that agroecological models are too restrictive to transform the agricultural sector as advocated but rather lure farmers into unproductive farming practices (Mugwanya, 2019). However, this opinion could be a result of the technical know-how, and the limited investigations on agroecology in Africa (Wezel et al., 2014, 2020), especially when the practice of agroecology requires a tailored understanding of plants, biogeochemical and climate relationships (Bezner Kerr et al., 2019), the knowledge that directly impact productivity that may not be readily available to smallholder farmers until they are adequately trained. Consequent to the claims of some that agroecological systems can only provide meager yields, a searchlight on the contribution of Africa to agroecology in the agricultural operations of the smallholder farmers revealed that around 33 million small farms exist in Africa accounting for more than 80% of all the farms on the continent (Hilson et al., 2021). Two-thirds of all African small farms are less than 2 ha, while 90% of all farms are smaller than 10 ha (Conway, 2011).

Largely, smallholder practitioners in Africa are women who engage in "low-resource" agriculture, providing the bulk of the region's grains and nearly all the root and tuber crops, including plantain and most of the legumes consumed (Altieri et al., 2012). Furthermore, smallholder agriculture and rural economic activities have been reported to provide over 60% of the livelihoods in Sub-Saharan African countries, and their effectiveness of operations is influenced by the choice of development strategy, which is hinged on the application of traditional systems (Okoh and Hilson, 2011). This strategy has sped up the pace of change in rural areas, demonstrating an effective and resilient indigenous agricultural strategy and serving as models of sustainability by promoting biodiversity, thriving without agrochemicals, and maintaining year-round yields in the face of societal pressures (Gomiero et al., 2011). Thus, the struggle and goals of rural movements are consistent with agroecology as a science since it upholds rather than undermines peasant logic, optimizes the design of local agricultural systems, and draws on local knowledge and resources. Additionally, agroecology is socially energizing because it depends on community involvement and horizontal techniques of information exchange to function (Levidow et al., 2014). This is evident in the UK government's Foresight Global Food and Farming project, where 40 initiatives and programs were examined in 20 African nations where sustainable crop intensification was pushed from the 1990s to the 2000s (Altieri et al., 2012). Crop enhancements, conservation agriculture, agroforestry, and soil preservation, integrated pest management, horticulture, aquaculture, livestock and fodder crops, and creative policies and collaborations were among the initiatives (Strapasson et al., 2020). The report revealed that by the beginning of 2010, these initiatives have produced improvements on over 12.75 million hectares and demonstrated benefits for 10.39 million farmers and their families. Since the agricultural yields increased by 2.13 times on average as a result of the introduction of new and improved varieties, food outputs from sustainable intensification were considerable (Mondal and Palit, 2021).

Agriculture contributes significantly to Kenya's economy, about 30% of the nation's Gross Domestic Product (GDP), over 60% of exports, 75% of the labor force, and more than 80% of industrial raw materials come from agriculture (Tomich et al., 2018). Although Kenyan smallholder farmers who are mostly engaged in crop production still require more resources to adopt sustainable agriculture and enhance their production efficiency, there is a paucity of empirical evidence and minimal research on the farmers' productivity (Abdulai and Hazell, 1996). Meanwhile, one of the most successful diversification strategies in Africa is agriculture-agroforestry-based practices. Evidence from Tanzania, Malawi, Zambia, Mozambique, and Cameroon revealed that the cultivation of maize alongside quick-growing nitrogen-fixing shrubs such as Tephrosia and Calliandra, increases total maize output of 8 t/ha as opposed to 5 t/ha under monoculture (Altieri et al., 2012). Similarly, the grain yield increase of up to 280 percent was recorded in Malawi when compared to the region outside of the tree canopy (Garrity et al., 2010). Furthermore, in the maize-Faidherbia system in Maradi and Zinder regions of Niger, where about 4.8 million hectares of Faidherbia were cultivated in fields containing up to 150 trees per hectare. The trees shielded maize plants from sweltering breezes, prevented the land from wind and water, while increasing agricultural yields. The success of this program encouraged the launch of such initiatives in other Sahelian countries to support the farmer-managed natural regeneration of Faidherbia and other species (Reij and Smaling, 2008).

Agroecological initiatives adopted in African countries also include the combined maize and legume farming, which is followed by rice in the following season as practiced by farmers in Madagascar to sustain soil fertility (Rodenburg et al., 2020). Madagascar farmers similarly employ the association of food crops (groundnut, Bambara bean, etc.) with *Stylosanthes guianensis* cv. CIAT 184 in rotation with rice on the poor soils, as directed by the Groupement Semis Direct de Madagascar (Michellon et al., 2011). Mostly, the presence of *Striga asiatica* in several regions of the nation is one of the main factors that instigated the practice of conservation agriculture, and thus served as a point of entry for the spread of agroecology techniques in the country (Michellon et al., 2011). In addition, the intercropping of maize with cover crops such as pigeon pea and *D. lablab* enables the farmers to produce three harvests even with greater yields in a season instead of the usual two harvests. Hence, the production index under conservation farming increased from 1.25 t/ha in 2004 to 7.0 t/ha in 2009, Thereby leading to significant decrease in the amount of work and time needed to expend on farm operations, and more smallholders embraced this program in the consequent cultivation periods (Owenya et al., 2011; Table 1).

Agroecological practices support biodiversity conservation and promote social justice

Farming practices rooted in agroecological principles are not new in Africa but rather have been the norm for millennia. Intercropping and crop varietal mixtures, crop rotations, weedy margins around gardens, mulches, ridging, bush fallows are common features of historical farming systems of Africa. In Uganda, coffee-banana systems are familiar; bananas provide shade to the coffee (Ssebunya et al., 2019). Similar to this is this cocoa-plantain system in Nigeria and Ghana, where the young cocoa plants benefit from the shade provided by the growing plantain (Dzomeku et al., 2008; Agbongiarhuoyi et al., 2016). In another instance, the system involves coffee and a few tree species like *Markhamia, Ficus* that provide timber, firewood, and fodder. There is no doubt that the root systems of the trees and the resulting litters provide mulch that support a wealth of soil microbes that contribute to a balanced edaphic system (Kalanzi, 2011). Predatory ants are often a constituent of mulched banana gardens and have been proven to constrain the population growth of banana weevils, [*Cosmopolites sordidus* (Germar)] in the plantation (Abera-Kalibata et al., 2006; Okolle et al., 2020). Furthermore, maize is often intercropped with beans or other legumes Intercropping entails the growing of crop varietal mixtures helps to reduce pest and disease incidence (Mulumba et al., 2012) while promoting a component of food security (availability). Soil and soil-water conservation practices like "soil basins", ridging, use of animal manures is widely used in many regions of Africa. The high vegetation diversity associated with agronomic practices based on agroecology sustains a wealth of biodiversity much of which is beneficial (pollinators, natural enemies, "soil engineers") and enables plant vigor.

While ecological farming may lessen many of the disservices associated with conventional farming, it should also be recognized that it is often associated with drudgery and may not be the ultimate solution to Africa's food crises. The current rates of population growth and urbanization may not allow for some techniques and much of the youthful population may opt for alternative forms of income, rather than farming. Declining soil fertility levels and erratic rainfall cannot be ignored; but call for the adoption of technological advancements that can cause significant increases in yield. What is perhaps needed is a well-thought-out mix of the best practices offered by both conventional and ecological farming. For instance, rather small-scale technologies like 'walking tractors' may be preferred over use of oxen; solar-powered water pumps for drip irrigation may be alternatives to rain-fed farming and large-scale irrigation schemes; motor-driven threshers and communal silos may be preferable over manual threshing and traditional homestead granaries. Such technological advancements may have a lower ecological footprint while reducing the labor burden and drudgery of traditional farming systems.

Conclusion and future applications of agroecology in Africa

Agroecology has been described as the cornerstone of sustainable agriculture. Beside its core ecological values in enhancing resource conservation and biodiversity leading to increased production efficiency, other essential features include the creation of an enabling environment for agroecological practices, which is achieved through responsible governance, circular and solidarity economy as shown in Figure 1. Hence, agroecology transcends the science and practice of agriculture to include social movement built on the tenets of ecology, food sovereignty, sustainability, justice, gender equity, farmer networks, resilience, resistance and access to land. It is a system that has been stimulated in response to the food and financial crises of 2008, as opposed to the detrimental effects of capital-intensive methods adopted during the so-called "Green Revolution." Hence, the innovations inherent in agroecological techniques are now gaining prominence due to its participatory approaches, community engagement and local knowledge as a guide. However, unlike the economic and institutional interests and support for agro-industrial based research and development in most African nations, less attention has been paid to research and development for agroecological and sustainable agriculture, which constitute a major arm of agroecology. This needs to be undertaken to overcome the barrier to the acceptance and spread of agroecological practices. Thus, an enabling environment that favors the implementation of agroecological-based farming techniques needs to be created by undertaking significant reforms in the policies, institutions, and the research and development agendas.

The alliances of various actors and organizations involved in the agroecological revolution is essential in enabling adequate coordination of the program. Apart from upscaling the knowledge and application of agroecological innovations, farmers will as well have increased access to government services, seeds, lands, and markets for their produce. Furthermore, the agroecological-based farming technique can be encouraged in African countries through the direct participation of farmers and scientists in the development of the research agenda to promote active engagement in the dissemination of innovative technologies using 'Campesino a Campesino model' where researchers and extension experts could play a pivotal facilitation role. This will enhance the development of sustainable agroecological alternatives that meet the needs of small-scale farmers and the low-income non-farming population, hence restoring the local food systems.

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.

TABLE 1 The agroecological practices in some African countries.

Country	Crop	Agroecological model	Implications of the intervention	References
Tanzania, Malawi, Zambia, Mozambique, and Cameroon	Maize	Maize cultivation in fast-growing nitrogen-fixing shrubs (e.g., Tephrosia and Caliandra)	increases total maize output of 8 t/ha as opposed to 5 t/ha achieved under monoculture	Altieri et al. (2012)
Niger, Malawi, and the southern highlands of Tanzania	Faidherbia	Faidherbia cultivated with tree crops	Increases yield while trees serve as shield crops from sweltering breezes and prevent wind and water erosion	Reij and Smaling (2008)
Madagascar	Maize, legume, and rice	Maize and legume intercropping, followed by rice cultivation	Sustain the soil fertility	Rodenburg et al. (2020)
	Groundnut, Bambara bean, rice e.t.c	Groundnut, Bambara bean, rice etc. with *Stylosanthes guianensis* cv. CIAT 184 in rotation with rice on the poor soils	Increases crop growth and soil fertility	Michellon et al. (2011), Altieri et al. (2012)
Tanzania	Maize, sorghum and millet	Conservation agricultural practices, organic fertilization	Significantly higher yields were obtained under organic fertilization than under no-fertilizations	Mkonda and He (2023)
	Maize, pigeon pea	Conservation agriculture, intercropping of maize with cover crops such as pigeon pea and *D. lablab.*	Results in greater yields, drought tolerance and produces three harvests instead of two harvests per season	Owenya et al. (2011)
Uganda	Maize	Cultivation of maize with velvet bean (*Mucuna pruriens*),	Generate organic matter and fix soil nitrogen. Increased maize yields. Reduced costs on labor and pesticides were completely removed	Kaizzi et al. (2004)
South Africa	Maize, potatoes, sugarcane	crop diversification, intercropping of maize with food crops, i.e., sugarcane, potatoes, and vegetables.	Enhancing soil fertility and crop yield, mitigating income and production risks	Hitayezu et al. (2016)
	Maize, sunflower	Application of rhizobacteria as soil treatment	Increased growth and yield, mitigation of drought stress	Bundy (1988), Adeleke and Babalola (2021), Agbodjato et al. (2021), Ojuederie et al. (2019)
Rwanda	Maize	Mulching, ridges,	Increase yield, resistance to drought	Uwizeyimana et al. (2018)
	Common bean	Narrow row planting	Increase crop growth and yield	Dusabumuremyi et al. (2014)
	Banana	Disease control through ‘complete diseased mat uprooting’ and ‘single diseased stem removal’	Control of *Xanthomonas* wilt of banana showed that ‘single diseased stem removal’ was an effective, less labor intensive and less costly method	Blomme et al. (2021)
Nigeria	Maize	Use of endemic atoxigenic strains, biochar, compost, plant extracts	Increase in plant growth and yield, management of fungal diseases of maize	Akanmu et al. (2020, 2021), Dlamini et al. (2022), Donner et al. (2009), Olawuyi et al. (2014)

(Continued)

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TABLE 1 (Continued)

Country	Crop	Agroecological model	Implications of the intervention	References
Zimbabwe	Maize	Conservation agriculture: direct seeding, rip-line seeding, and seeding into planting basins on maize grain yield, soil health and profitability across agroecological regions in Zimbabwe	Reduced soil erosion and bulk density, and increased soil water content. Greater macrofauna abundance and diversity than conventional agriculture	Mafongoya et al. (2016)
Zambia	Maize	Sustainable agricultural practices involve agroforestry, intercropping, and overcrops.	Increased productivity and efficient soil management. Results in the enhanced relationship between land tenure and the use of mulching, tree planting, manure and mineral fertilizers	Nkomoki et al. (2018)
Ghana	Apple, cocoa	Agroecological practices such as organic fertilizers, crop rotation, organic pest and weed control, mulching, cover crops, trees, soil and water conservation	Organic certification increases agroecological practice use. Improvement of soil nutrient	Kleemann and Abdulai (2013), Quaye et al. (2021)
Lesotho	Maize	Crop diversification and livestock integration	High-value intercrops such as pumpkins recorded higher farm economic margin than their monocropping counterparts.	Seko and Jongrungrot (2022)
Senegal	Peanuts	Indigenous agroecosystems through processes of biodiversification	Boosted soil fertility and agricultural productivity	Faye and Braun (2022)
Benin	Bananas and Plantain	Crop association, mechanical destruction of diseased plants, banana plantation in shallows, trap plants, crop rotation, compost use and poultry manure use.	Sustainable production and management of plant diseases caused by Fusarium sp., nematodes and banana bunchy top virus	Dassou et al. (2021)
Burkina Faso	Cereal - legume	(a) Use of organic matter with or without micro-dose mineral fertilization (b) the localized application of organic manure in planting pits dug into hard pan land (zaï), with and without cereal-legume rotation	Enhances soil microbiological activities	Somda et al. (2022)
Mali	Cereal and legumes	Crop residue management, cereal-legume cropping rotations and intercropping, biological pest control through predator rearing, agroforestry, and the use of trees as fences	improved yields due to some better management of agricultural resources.	Paracchini et al. (2020)

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EDITED BY
Bekele Hundie Kotu,
International Institute of Tropical Agriculture, Ghana

REVIEWED BY
Getnet Assefa,
Land O'Lakes, Inc., United States
Loïc Sauvée,
UniLaSalle, France
Bayeh Mulatu,
Food and Agriculture Organization of the United Nations, Ethiopia

*CORRESPONDENCE
Kindu Mekonnen
✉ k.mekonnen@cgiar.org

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Research for development approaches in mixed crop-livestock systems of the Ethiopian highlands

Kindu Mekonnen[1]*, Peter Thorne[1], Million Gebreyes[1], James Hammond[2], Melkamu Bezabih[1], Seid Ahmed Kemal[3], Lulseged Tamene[4], Getachew Agegnehu[5], Rabe Yahaya[6], Aster Gebrekirstos[7], Minh Thai[8], Kalpana Sharma[9], Aberra Adie[2] and Anthony Whitbread[10]

[1]International Livestock Research Institute, Addis Ababa, Ethiopia, [2]International Livestock Research Institute (ILRI), Nairobi, Kenya, [3]International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco, [4]Alliance Bioversity-CIAT, Addis Ababa, Ethiopia, [5]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Addis Ababa, Ethiopia, [6]International Maize and Wheat Improvement Center-CIMMYT, Addis Ababa, Ethiopia, [7]World Agroforestry Centre, Nairobi, Kenya, [8]International Water Management Institute (IWMI), Accra, Ghana, [9]International Potato Center, Nairobi, Kenya, [10]International Livestock Research Institute, Dar es Salaam, Tanzania

This study presents processes and success stories that emerged from Africa RISING's Research for Development project in the Ethiopian Highlands. The project has tested a combination of participatory tools at multiple levels, with systems thinking and concern for sustainable and diversified livelihoods. Bottom-up approaches guided the selection of technological interventions that could address the priority farming system challenges of the communities, leading to higher uptake levels and increased impact. Joint learning, appropriate technology selection, and the creation of an enabling environment such as the formation of farmer research groups, the establishment of innovation platforms, and capacity development for institutional and technical innovations were key to this study. The study concludes by identifying key lessons that focus more on matching innovations to community needs and geographies, systems orientation/integration of innovations, stepwise approaches to enhance the adoption of innovations, documenting farmers' capacity to modify innovations, building successful partnerships, and facilitating wider scaling of innovations for future implementation of agricultural research for development projects.

KEYWORDS

action research, systems thinking, innovations, partnership, scaling

1. Introduction

In developing countries, the demand for food-feed energy has increased because of a rapidly growing population. This situation has called for a joint effort to seek potential and impactful approaches and interventions. Sustainable intensification (SI) has been proposed as one of the strategies/approaches to meet the current needs and ensure future food-feed-energy security (Pretty and Bharucha, 2014). It is an approach using innovation to increase productivity on existing agricultural land with positive environmental and social impacts (Loos et al., 2014; Pretty and Bharucha, 2014; Donovan, 2020). SI takes into consideration the impact on overall farm productivity, profitability, stability, production and market risks, resilience, and the interests and capacity of individual farmers to adopt innovations. Sustainable intensification is not limited to environmental concerns but also includes social and economic criteria such as improved livelihoods, equity, and social capital (Loos et al., 2014; Pretty and Bharucha, 2014; Donovan, 2020).

The concept of SI has evolved and become a subject of debate, although there is agreement among wider groups of experts on its contribution to increasing productivity and improving sustainability in smallholder mixed-crop livestock systems. Various approaches/tools/frameworks have been used by different scholars to assess the performance of SI at the field level for individual technologies (Musumba et al., 2017) and at the farm-to-landscape/district level for multiple technologies (Hammond et al., 2021). The SI assessment findings on multiple crops, livestock, and NRM technologies by Hammond et al. (2021) showed more synergies than tradeoffs among SI domains.

The conventional approach to agricultural research with a linear model of technology being generated by research, transferred through agricultural technologies extension to reach farmers has been found inadequate to address the challenges facing agricultural development in sub-Saharan Africa (Ellis-Jones et al., 2017). As a result, different participatory-oriented and integrated agricultural research for development (IAR4D) approaches have received due attention in the developing world to implement SI programs, address context-specific problems of smallholder farmers, and enhance interaction and adoption of agricultural technologies. IAR4D attempts to combine conventional research approaches, the co-creation of scientific knowledge, and mechanisms of interaction with agricultural technology innovators, beneficiaries, and other actors (Zonta et al., 2021). In addition, it fosters the development of research approaches that are inclusive of all relevant actors, markets, and end users' demands, with due consideration for value chains (Adekunle and Fatunbi, 2014).

As the name implies, integration is at the heart of IAR4D. Integration is envisaged along four lines as follows: integration of stakeholder perspectives, knowledge, and actions; integration of mutual and collective learning experiences; integration of analysis, action, and change along sustainable development goals; and integration of analysis, action, and change along different socioeconomic and spatial organizations (Adekunle and Fatunbi, 2014). Integrations along these four lines are expected to lead to the integration of research and development, technological solutions with institutional and infrastructure solutions, production, and gender and social inclusion considerations (Adekunle and Fatunbi, 2014). The IAR4D works with "principles and guidelines that brings [sic] stakeholders with different background and interests to analyze agricultural challenges, develop solutions, and translate them into achievable targets" (Ngaboyisonga et al., 2017).

The study aimed to share IAR4D approaches that enabled smallholder farmers to apply SI technologies, present key findings, and share lessons learned through the implementation of the first phase (2012–2016) and the second phase (2017–2021) of the Africa RISING project in the Ethiopian Highlands and to draw implications for future project design and for the theory of agricultural development.

2. Materials and methods

2.1. Project description

Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) is a program that consists of three projects, namely, West Africa (WA), East and Southern Africa (ESA), and Ethiopian Highlands projects. The program operates in six African countries and is managed by IITA, ILRI, and IFPRI. The United States Agency for International Development (USAID), as part of the U.S. government's Feed the Future initiative, has been funding the program since 2012.

Through action research and development partnerships, Africa RISING aimed to create opportunities for smallholder farmers to move out of hunger and poverty through sustainably intensified farming systems that improve food, nutrition, and income security, particularly for women and children, and conserve or enhance the natural resource base (International Livestock Research Institute, 2020). Africa RISING in the Ethiopian Highlands operated in eight research intervention kebeles (the lowest administrative units in Ethiopia) that spread across the four main highland regions (Amhara, Oromia, Tigray, and SNNP). The average number of households in the Africa RISING operational areas is ∼860. The project's first phase was implemented from 2012 to 2016. The second phase became operational in 2017 and continued until 2021. An approach based on Integrated Agricultural Research for Development (IAR4D) methods was applied both in the first and second phases of the project.

2.2. Selection of project sites

Representatives from multiple institutions, such as the donor (USAID, Washington, USA), the implementing agency in Ethiopia (ILRI), and the implementing agency for sister projects such as the West Africa project and the East and Southern Africa project, co-developed a research framework in 2012 to serve as a guideline or reference document for the operation and implementation of the Africa RISING program (International Livestock Research Institute, 2012). A set of three broad site selection criteria at the woreda (district) level was then established for the four main Ethiopian Highland regions (Amhara, Oromia, SNNPR, and Tigray). These woredas, which had more than 25% of their land area under wheat cultivation, and were located between 1,900 and 2,400 m above sea level (m.a.s.l.), participated in USAID's main Feed the Future investment for the Highlands, and the Agricultural Growth Program (AGP). Within each of these woredas, two representatives "research kebeles" were jointly selected as platforms for the IAR4D activities to be implemented by the project (Table 1).

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TABLE 1 Climate, soil, and crop production characteristics of the eight Africa RISING kebeles in the Ethiopian Highlands.

Region	Woreda	Kebele	Elevation range	Annual rainfall (mm)	Mean annual max temp (°C)	Mean annual min temp (°C)	Dominant soil type	Main crops	Priority issues/problems
Amhara	Basona	Goshe Bado	2,001–3,800	912–1,127	22	9	Cambisols/vertisols/lithosols	Wheat, faba bean, barley, potato	Land degradation, soil depletion, and low crop and livestock productivity
		Gudo Beret	2,500–3,800	1,128–2,228	20	6	Regosols/cambisols/lithosols		
Oromia	Sinana	Salka	2,000–2,800	950–1,000	20	6	Vertisols/fluvisols/nitisols/	Wheat, faba bean, emer wheat[b]	Wheat-dominated mono-crop system, poor human and livestock nutrition, and crop diseases
		Ilu Sanbitu	2,000–2,500	950–1,000	22	8	Vertisols		
SNNPR[a]	Lemo	Jawe	2,000–2,300	1,100–1,120	23	10	Vertisols	Wheat, faba bean, teff[c], and enset[d]	High population, feed shortage, soil acidity, and enset disease
		Upper Gana	2,000–2,500	1,120–1,170	22	10	Vertisols/nitisols/cambisols		
Tigray	Endamekoni	Emba Hazti	2,000–3,800	700–750	15	6	Cambisols/regosols/lithosols	Wheat, barley, faba bean, potato	Shortage of protein-rich fodder, few income diversification options, water scarcity, soil depletion, and low crop yields
		Tsibet	2,500–3,800	700–750	12	4	Cambisols/regosols/lithosols		

Source: Ellis-Jones et al. (2013): EIAR GIS (2015, personal communication); Authors' own expert knowledge.
[a]Southern Nations, Nationalities, and Peoples' Region.
[b]Triticum dicoccum.
[c]Eragrostis tef.
[d]Ensete ventricosum.

TABLE 2 Average annual dry biomass and nutritive value of selected forage options at the project sites in the Ethiopian Highlands observed from 2013 to 2020.

Forage types	Scientific names	Observed dry matter (t ha^{-1})	Reference yield (t ha^{-1})*	CP (% DM)	ME (MJ/kg DM)	IVOMD (%)	Observed CP yield (t ha^{-1})
Oat	*Avena sativa*	14.5	12.2	10.5	8.7	60	152.3
Vetch	*Vicia villosa*	9.6	5	18.0	10.8	67.4	172.8
Lablab	*Lablab purpureus*	5.3	6.1	16.0	8.6	63	84.8
Sweet lupin	*Lupineus albus*	3.4**	3.7	21.0	9.26	65.5	71.4
Alfalfa	*Medicago sativa*	15.3	18	22	11.4	80	336.6
Brachiaria	Brachiaria hybrids, Var Mulatto II	7.5	8.5	19	7.8	57.5	142.5
Phalaris	*Phalaris aquatica*	8.5	14	9.0	7.4	56	76.5
Fodder beet	*Beta vulgaris*	20.2	31	7.5	11	79	151.5
Desho grass	*Pennisetum pedicellatum*	8.4	10	11	7.5	62	92.4
Tree lucerne	*Chamaecytisus pamensis*	8.7	10.2	22.5	9.0	70	195.8
Faba bean—oat intercropping	*Vicia faba–Avena sativa*	5.5***	NA	10	8.5	64	55.0
Oat-vetch mixture	*Avena sativa–Vicia villosa*	15	12	15	9.5	66	225.0
Desho grass—vetch intercropping	*Pennisetum pedicellatum–Vicia villosa*	11	NA	14	9.2	65	154.0

*Reference average yields were derived from Feedipedia: https://www.feedipedia.org/ and the Tropical Forages Database: https://www.tropicalforages.info/; NA, not available.
**The number in the table refers to biomass production from sweet lupin.
***This refers to the grain yield of faba bean and biomass of oat.

2.3. Farming system diagnosis

The project coordination team involved leading researchers from CGIAR centers (ILRI, IWMI, CIAT, CIP, CIMMYT, ICRAF, ICARDA, ICRISAT, and IFPRI) and local partners to design and implement the subsequent IAR4D activities. Development agencies, such as public extension services and locally operating non-governmental organizations (NGOs) were included in the cohort of local partners at this very early stage to ensure that their priorities would be embedded within those of Africa RISING and to develop a strong sense of ownership among them. The broader Africa RISING team conducted diagnostic exercises in the selected sites using eight tools and methods (e.g., Lunt et al., 2018) to understand the farming systems and identify major challenges and opportunities. The tools/methods used were Rapid Telephone Survey (RTS), Sustainable Livelihood Asset Evaluation (SLATE), Participatory Community Analysis (PCA), IMPACTlite survey, Agro-ecological knowledge Tool (AKT5), Feed Assessment Tool (FEAST), Technology Fit (TECHfit), and Market/Value chain studies. The priority issues identified by the communities were then used as a basis for formulating a set of thematic research areas. The Africa RISING Agricultural Research for Development Team (ARAR4DT) used these themes as a framework for developing action research protocols to directly address the concerns of communities and development partners. Regular monitoring of IAR4D activities and mid- and end-term evaluation of project performances were carried out throughout the life (Phases I and II) of the project (Pound et al., 2015; Negra et al., 2020).

2.4. Clustering of farming system constraints and identification of thematic areas

The constraints identified at the project sites covered different socioeconomic, biophysical, and climatic dimensions. The most important constraints identified included climate variability, low crop yields (< 1 t ha^{-1}), soil fertility depletion, erosion, poor drainage, high prices and poor access to fertilizer, crop pests, weeds and diseases, postharvest losses (30%−40%), lack of improved farm implements, acute shortage of animal feed, poor access to veterinary drugs and animal health services, seasonal water scarcity, poor household nutrition, shortage of wood for fuel, and weak links to markets (Ellis-Jones et al., 2013). Experiences from other IAR4D projects, such as the African Highlands Initiative (German et al., 2012), were reviewed to understand how they developed frameworks for integrated research thematic areas and protocols. Accordingly, the ARAR4DT then clustered constraints and identified seven key thematic areas based on (i) feed and forage development, (ii) field crop varietal selection and management, (iii) integration of high-value

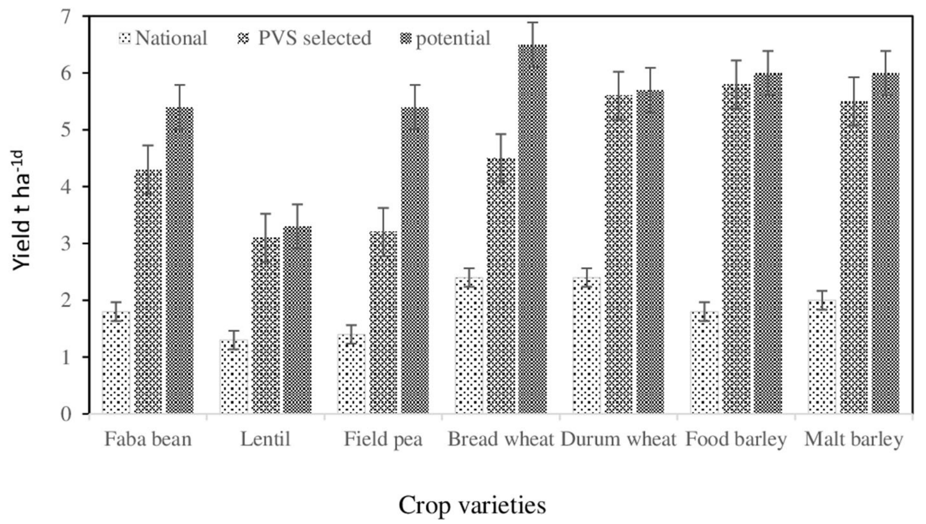

FIGURE 1
Potential, participatory varietal selection (PVS) and national average yield difference in the Ethiopian highlands.

products into mixed farming systems, (iv) improved land and water management for sustainability, (v) improving the efficiency of mixed farming systems through more effective crop-livestock integration, (vi) cross-cutting issues and opportunities (markets, gender, and nutrition), and (vii) knowledge management, sharing, and capacity development. The ARAR4DT then designed 17 primary action-oriented research interventions that addressed one or more of the seven identified themes (Lunt et al., 2018). Aspects of pest and disease management were addressed under the theme of field crop varietal selection and management.

2.5. Identification and validation of SI technologies

A menu of SI technologies and their performance requirements was presented to communities to engage them in on-farm research initiatives. Africa RISING encouraged the elective engagement of participating farmers, including women and youth, in the SI technologies to ensure context-specific and demand-driven focus. Farmers who were interested in participating in one or more SI technologies and who could allocate suitable parcels of land for on-farm research were identified and registered during the community consultation meetings. Farmers who were interested in participating in the different SI technologies were grouped into farmer research groups (FRGs). The CGIAR centers, Africa RISING site coordinators, local partners, and farmers established different on-farm action research experimental plots in 2013 and continued the research thereafter. The number of farmers that directly engaged in crop varietal selection, feed and forage options, and natural resource management was over 2,183. Biophysical/biological and socioeconomic data that matched each of the SI technologies were collected. Review and planning workshops were organized regularly to evaluate research results and plan for follow-up experimentation.

2.6. Demonstration of best SI technologies

Different SI technologies were demonstrated within and outside the Africa RISING research kebeles to encourage user adoption. Validated SI technologies were demonstrated using three approaches.

- Model farmers—These are farmers who have participated in the validation of different SI technologies and have successfully managed them. Most of these farmers have benefited from SI technologies and have shown interest in allocating more land and resources to maintain and expand these technologies on their farms. These model farmers are visited by neighboring farming communities and other farmers from different localities, and they serve as one of SI technology demonstration sites to promote wider adoption.
- Farmer training centers (FTCs)—FTCs have been established by the Ethiopian government in different kebeles to demonstrate technologies and equip farmers with essential farming knowledge and skills. In the context of the Africa RISING project, the existing FTCs have been useful niches to establish research for development activities and evaluate various crop, livestock, and natural resource management technologies. In addition, they have played significant roles in multiplying forage and improving crop varieties.
- Contracted land—SI technology demonstrations on mother-baby plots (crop and forage varieties) were established on contracted land in different Africa RISING project research kebeles. These plots consist of different SI technologies. Farmers visited during field days and other events to observe the use of SI technologies on mother-baby plots.

TABLE 3 Uptake and adoption rates of various technologies promoted by the Africa RISING program.

Site (Woreda)		Basona Worena	Endamehonei	Lemo	Sinana
Number of surveys		148	213	254	164
PVS	Number trialed	111	144	116	133
	% continued using	79	84	77	87
	% doubled use	43	48	13	32
Seed supply	Number trialed	24	18	26	29
	% continued using	92	67	54	62
	% doubled use	21	44	0	17
Cultivated forage	Number trialed	66	95	122	48
	% continued using	65	74	87	40
	% doubled use	41	37	7	15
Fruit trees	Number trialed	35	64	102	19
	% continued using	43	95	94	68
	% doubled use	23	28	6	0
Soil testing	Number trialed	34	49	1	6
	% continued using	97	94	0	50
	% doubled use	9	4	0	33
Water pumps	Number trialed	0	5	8	0
	% continued using	NA	100	50	NA
	% doubled use	NA	0	0	NA

Source: a household survey conducted in 2018 in Africa RISING sites in the Ethiopian Highlands.
The number of households that trialed each technology is reported and can be compared to the total number of households surveyed in each community. The proportions of those who continued to use the technology at a similar rate and the proportions of those who continued to use the technology at an increased rate (doubled use or more) are also reported.
PVS, participatory variety selection; NA, not available.

Model farmers, FTCs, and contracted land technology demonstration approaches contributed to the utilization of SI technologies in many ways. First, they enabled farmers to visit and observe the performance and benefits of the SI technologies because of their proximity to villagers. Second, the model farmers generated more interest and increased their willingness to practice the SI technologies as a result of sharing their successes. Third, they served as a means for the quick transfer of knowledge and information that improved the utilization of SI technologies. In most cases, farmers became convinced when they heard from those who had become successful by adopting/practicing SI technologies.

2.7. Exploration of different options for seed multiplication of crop and forage varieties

Access to improved crop and forage seeds is a challenge for farmers in many parts of Ethiopia. Compared to crop seed suppliers, forage seed suppliers are very few, and their capacity to supply adequate seed is limited. Cooperatives, unions, model farmers, NGOs, local universities, and research centers were identified as potential partners to multiply crop and forage seeds in different Africa RISING sites. These partners initially received starter-improved crop and forage seeds for multiplication and later used the seeds to distribute to large numbers of farmers on a seed-revolving system arrangement. Farmers who received improved crop and forage seed were expected to either return equivalent amounts of seed or pay cash for their cost. The Africa RISING project supported informal seed multiplication by employing capacity development initiatives, like the provision of training, organizing field visits, and producing and delivering informal seed multiplication guidelines. The quality of seed received from revolving seed arrangements was carefully monitored by site coordinators and experts from local partners.

2.8. Facilitation of a broader scaling of SI technologies

Africa RISING worked with a wide range of partners during the first phase of its action research and the second phase of scaling up. The following steps were taken to develop and maintain partnerships and to facilitate the scaling of SI technologies.

- Validated SI technologies ready for scaling were identified;
- Information on validated SI technologies was packaged into fact sheets;
- Contact with potential development scaling partners was established to share research findings and requirements for the SI technologies;

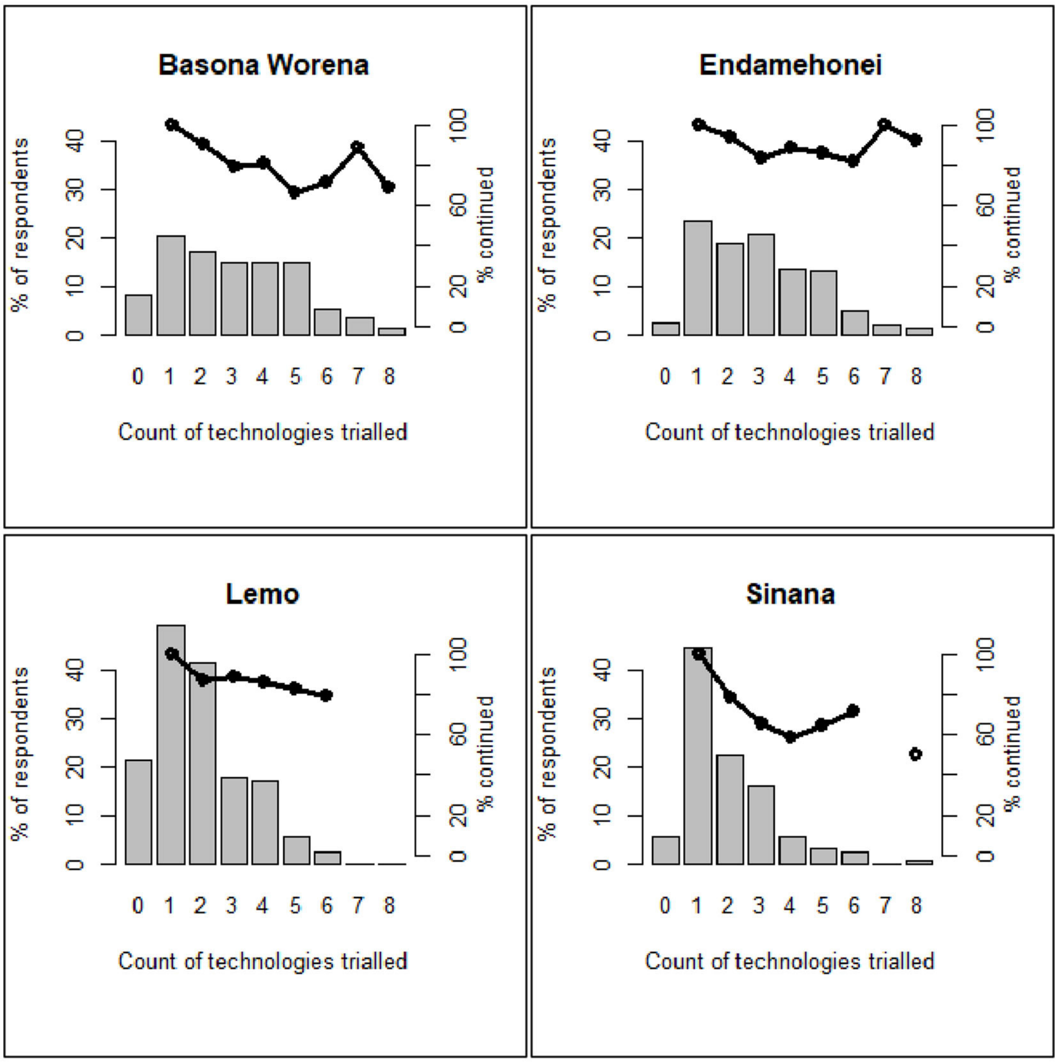

FIGURE 2
The bar charts show the number of technologies trialed by households, and the line chart on the secondary vertical axis shows the average percentage of technologies which were continued to be used by households after the year 2018. The four plots each represent one of the four study sites (woredas).

- A template to collect information on the capacity of each of the development partners to scale SI technologies was developed;
- Contacts were identified at the site level to facilitate communication, supervision, data collection, and evaluation;
- Training was provided to experts, development agents, and farmers on scalable SI technologies;
- Starter seeds of improved crop and forage varieties were purchased and provided to cooperatives, unions, model farmers, extension—FTCs (farmer training centers), NGOs, and local universities for multiplication and distribution to farmers on a revolving seed arrangement.
- Seeds of different improved crop and forage varieties and multiplication approaches were tested to recommend the best model for the extension system at the respective project sites.
- Exchange visits and training were organized for development partners to accelerate the scaling up of Africa RISING through the validated crop, livestock, and natural resource management innovations.

2.9. Enabling conditions applied during the research and scaling process

2.9.1. Formation of research groups

At the four research sites, eight FRGs related to SI technologies were established and named accordingly (Mekonnen et al., 2017). Each FRG consists of 25–30 male and female farmers representing a range of social groups. The FRGs were established based on farmers' common interests and technology choices and were key in enhancing cross-learning and increasing the overall efficiency of innovations. Experiences from elsewhere, such as the International Institute of Tropical Agriculture (2003),

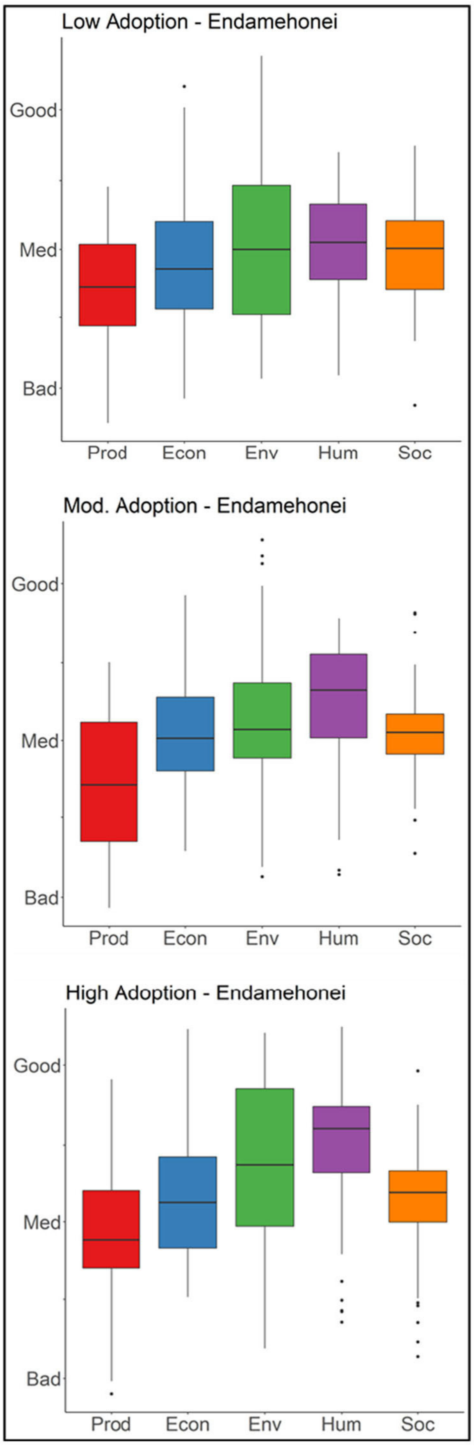

FIGURE 3
Summary of 28 indicators relating to the domains of sustainable intensification: agricultural productivity, economics, environment, human welfare, and society. Indicator scores were re-scaled according to locally thresholds. The three panels differentiate households according to the number of SI technologies they adopted, where low adoption entailed zero or one technology, moderate adoption entailed two technologies, and high adoption entailed three or more technologies. Differences between the study sites (woredas) were great, and so the results shown here are for Endamehoni.

show that FRGs are increasingly becoming the vehicle through which farmers pursue broader concerns, initiate new activities, organize collective action, and expand links with external organizations.

2.9.2. Establishment of innovation platforms

The ARAR4DT established four strategic innovation platforms (IPs) at the woreda level and eight operational innovation platforms (IPs) at the kebele level. An innovation platform is a stakeholder forum established to facilitate interaction and learning among stakeholders, often selected from a commodity chain or system, to engage in the participatory diagnosis of problems, joint exploration of opportunities, and investigation of solutions, leading to the promotion of innovation along a targeted value chain (Homann-Kee et al., 2013). The strategic IPs were established through the engagement of local decision-makers, public extension service providers, NGOs, universities, local research centers, market dealers, farmer representatives from the two Africa RISING research kebeles, breweries, development programs, community-based organizations (CBOs), and agro-food processors. Participating stakeholders were targeted to create good synergies for joint action research and to increase their capacity to contribute to SI issues specific to the local context.

The kebele operational IPs consisted of the kebele administrators, development agents, and farmers participating in the project's research for development activities. The role of these IPs was to coordinate research for development activities, identify challenges and opportunities for agricultural innovation or development, encourage interactions between the public, private, NGOs, and CBOs, and arrange and coordinate field days, evaluations, and training (Ellis-Jones et al., 2013).

The smooth and regular operation of innovation platforms requires resources and commitment. Innovation platforms can be established for a certain purpose in the short or long term. The Africa RISING Innovation Platforms had focal points composed of different local actors/partners. The focal points/partners were responsible for leading the platforms. Meetings were organized on a rotating basis in different institutions, such as extension offices, local universities, research centers, and district and zonal administration bureaus. Local partners in the different Africa RISING sites have already recognized the importance of the platforms and have used them for planning, communication, and cross-learning purposes.

A number of farmer research groups (FRGs) were formed within the operational IPs and clustered around specific research themes (e.g., feeds and forages), as a channel to link the IPs to the households participating in the action research.

2.9.3. Capacity development

Africa RISING promoted capacity building for human resource development and strengthening of local partner organizations in various ways, all designed to respond to demand from local partners and to create an enabling environment for knowledge exchange and innovation. These included the following:

- Co-designing of the research agenda for the season;
- Mid-season and end-of-season field days to demonstrate research interventions and provide feedback regarding the suitability and performance of technologies;
- Exchange visits for cross-learning and sharing of knowledge and information;
- Short-term training to familiarize project partners with the use of survey tools, research approaches, functioning of innovation platforms, operation of improved technologies and management practices, and simulation modeling;
- Placement of MSc and Ph.D. students to undertake field research as part of their studies;
- Workshops to develop and review research plans, co-develop research ideas, and share project research results and information;
- Multiple communication and learning channels, such as websites and learning events, to inform, engage with, and influence a wide audience;
- Workshops to produce briefs, journal articles, and other products;
- Field monitoring by the Africa RISING project coordination team to increase the awareness and participation of site-level partners regarding the Africa RISING research activities;
- Use of site and assistant site coordinators to run action research activities and strengthen communication and linkages between local and CGIAR partners;
- Provision of research infrastructure facilities to facilitate the generation of research evidence, implement the action research protocols, and demonstrate commitment to partners;
- Organizing feedback loops to improve research design and outcome pathways.

3. Results

3.1. Biomass production, nutritional value, and effect of forage supplementation on livestock performance

Cultivated forages and fodder trees validated under farmers' management conditions in sole and mixed/intercropped arrangements at the Africa RISING project sites included oat-vetch mixture, sweet lupin, alfalfa, fodder beet, desho grass, lablab, brachiaria, phalaris, vetch-desho grass mixture, faba bean-forage intercrop, and tree lucerne (Table 2). The productivity of the cultivated forage and fodder tree options and their nutritional values varied from site to site because of climatic, edaphic, and management factors. The average biomass yield (t DM ha^{-1}) and the nutritive value obtained across the Africa RISING sites under farmers' fields and management conditions are indicated in Table 2. Most of the forage and fodder trees evaluated in the Africa RISING project sites have high herbage biomass yields with good nutritional quality (Mekonnen et al., 2021). Validating this type of forage and fodder tree species is very important given the current feed supply and quality constraints in the highlands of Ethiopia. For lactating cows, milk yield increased by more than 50% when their diet was supplemented with 2 kg dry matter of oat-vetch mixture per day. In fattening sheep, supplementation with 300–400 g/day of tree lucerne hay feed increased daily body weight gain by 70 g.

3.2. Yield of field crop varieties

The Africa RISING project has introduced different varieties of cereals, legumes, oilseeds, and tuber crops and validated them through participatory varietal selection (PVS) approaches with farmers. PVS has been shown to increase crop yields compared to conventional approaches. For instance, improved potato varieties introduced by the project and validated through PVS were high yielding (32–53 vs. 2–8 t ha^{-1}), early maturing (98 vs. 120 days), and tolerant to late blight (International Livestock Research Institute, 2017). The yield of cereal and legume varieties obtained through PVS was also higher than the national average crop yields (Figure 1). PVS and other research activities were closely followed at different stages of research that included selection, application of proper agronomic practices, and postharvest techniques, which fostered yield increases in PVS as compared to conventional production systems.

3.3. High-value fruit trees

Africa RISING accessed grafted seedlings of five improved avocado varieties (Ettinger, Fuerte, Hass, Nabal, and Reed) and validated the performance of the varieties with farmers in its operational areas. The improved avocado varieties are productive and able to bear fruit within 2–3 years period. They are also short, thus making harvesting very easy. Survival rates for avocado varieties in Africa RISING sites were found to be 90%—100%. Fruit yield varied among the five varieties. The mean yield for Ettinger, Fuerte, Hass, and Reed was 45 kg per tree, while it was approximately 90 kg per tree for Nabal (Mokria et al., 2022).

3.4. Soil fertility management

The research was conducted on crop responses to combinations of multiple macronutrients and micronutrients such as NPSK, NPSB, and NPS in wheat-based cropping systems. It was possible to identify soil-specific best fertilizer blends and rates for wheat in the eight targets Africa RISING research kebeles. The new recommendations boosted yields by two to three times, even in previously "non-responsive" soils, and included N-P-K plus sulfur, zinc, and boron. As a result of the research on the targeting of micronutrients in fertilizers, a new national initiative has been catalyzed to deliver these innovations nationwide (Amede et al., 2022).

3.5. Small-scale mechanization

Different small-scale mechanization technologies for land preparation and planting, harvesting, post-harvest processing, and micro-irrigation have been tested and promoted on smallholder farms in the four Africa RISING operational regions of Ethiopia. These mechanization technologies, powered by low-horsepower two-wheel tractors (2 WT), include plowing, planting, harvesting, threshing, shelling, water pumping, and transport services. The following are examples of research results from the small-scale mechanization work:

(a) Maize and wheat productivity gains of 16%−44% and 10%−25%, respectively, have been documented on farms using 2 WT technologies compared to conventional *Maresha*-based practices (International Livestock Research Institute, 2020);
(b) Two-wheel tractor-driven harvesting of crops such as wheat saved time and increased gross margins by 55%−89% for farmers who received harvesting services as compared to those who used traditional (human labor) methods;
(c) Service providers of 2 WT generated income from maize shelling and wheat and barley threshing. For example, service providers generated US$9,180.89 and US$5,959.85 through wheat threshing and maize shelling services, respectively, during the January–April 2020 dry season.

3.6. Soil and water management

Implementation of integrated soil and water conservation (SWC) practices at the landscape scale reduced sediment yield by 74%. Runoff and soil loss were reduced by an average of 27 and 37%, respectively, due to SWC practices at the plot level (Yaekob et al., 2020). Improved water lifting technologies increased farmers' ability to irrigate high-value crops and improved household nutrition. Irrigated fodder biomass increased by 14% dry weight when farmers were guided in their irrigation practices by the wetting front detectors at the Lemo Africa RISING site.

3.7. Adoption of technologies and enabling conditions

Data collected from a survey in 2018 on the number of households that tried each intervention, and then the number of households that kept using those interventions are presented in Table 3. Interventions had a high rate of uptake. Although there was variation across study sites and between the technologies, ∼80% of farmers continued to use the interventions they trialed, and ∼30% doubled the extent to which they used them. A decline in technology use after the project support is withdrawn is possible, but these uptake and continuation rates are likely to represent a critical mass for longer-term retention. Most commonly, households tried one or two technologies, but approximately one-third of the study population trialed three or more technologies. Continuation rates for households trialing more technologies remained high (Figure 2).

To explore possible reasons for the relatively high technology uptake rate, a regression model was built using variables for the study site, household assets (land, livestock, and income), household head education, and enabling conditions influenced by the Africa RISING project. The variables used to describe enabling conditions were the number and quality of training sessions attended, the number of support groups joined, the reasons given for the selection of technologies, and the number of peers with whom good practices were shared. The indicators of enabling conditions were all found to have a positive relationship with the number of technologies, significant at the p-level of <0.001. The study site also had a major effect on adoption, with the number of technologies remaining significantly lower in Sinana as compared to the other locations (which may be related to the more cereal-focused agricultural system). Interestingly, household wealth had a smaller effect, with only livestock ownership having a significant influence on technology continuation and a non-linear relationship with the land area as implied by the model findings.

3.8. Stakeholder engagement

As a project working at the boundary between research and development, Africa RISING took an approach that engaged multiple stakeholders. The processes of engagement led to a number of results/outcomes that are both hard to measure and essential for creating the enabling environment for SI to occur. The main mode of engagement was through innovation platforms (IPs), supplemented by communication and capacity-building activities. The IPs played different roles, including the following:

- Setting research agendas: In Basona woreda, for example, during a strategic IP establishment meeting, IP members requested a focus on watershed development issues as land degradation posed a major problem in their district;
- A feedback mechanism for researchers: In Endamehoni woreda, for example, during the second strategic IP meeting, members suggested reducing the number of varieties for participatory varietal selection and focusing on just a few potential ones. Such feedback was essential for the researchers to adjust their research approach and process and maintain a response-demand-led approach;
- Partnership development for scaling: In the Lemo district, for example, during the second strategic IP meeting, scalable technologies, namely micro dose fertilizers, water lifting technologies for irrigation, potato feeds, and livestock feeds, were presented. IP members from the CG centers, regional research institutes, and a local university agreed to provide technical capacity building for community organizations. The district agricultural office and local NGOs committed themselves to mobilize resources for and empowering farmers. Africa RISING agreed to provide starter seeds and some other material provisions. The report given during the subsequent IP meeting showed that, as a result, members took

their decision-making further and committed themselves to continuing the activities during the next planting season.

3.9. Scaling and sustainability

The Africa RISING project's 2015 mid-term evaluation report noted that the action research conducted at the four research sites and the innovation platforms built around them were the nuclei for scaling out and scaling up innovations (Pound et al., 2015). Hence, the initial research phase and associated spontaneous scaling activities enabled a well-developed niche innovation system for Africa RISING-validated technologies. Long-term and evidence-based relationships, complemented by the trust of a wide range of local actors, paved the way for a subsequent, more deliberate scaling initiative in the second phase (Pound et al., 2015). For example, in one of the intervention sites, in the Tigray region, the district and zonal experts were involved in site selection, mid- and end-season evaluation of wheat, and participatory varietal selection of faba bean and potato. The new varieties and their management practices led to an enormous productivity gain (58, 47, and 88% for faba bean, bread wheat, and potato, respectively) as compared to the local, and even regional, standards. When the district experts observed these results, they returned to their office and documented all the innovations so that they could be used as benchmarks for production to be embedded in their future planning. These officials also went on to share these plans with the regional Bureau of Agriculture, using the documented evidence. This resulted in the recognition of the achievements by the regional government, which used the district experience as a benchmark for the regional expansion of wheat and potato production.

In line with its commitment to promoting SI, Africa RISING commissioned an assessment to better understand the balance between production and sustainability outcomes of the project. In a 2018 household survey, 28 indicators were collected in relation to five domains of sustainable intensification: agricultural production, economic, environmental, human welfare, and social. These indicators were rescaled and are presented in Figure 3 (which shows results for the Endamehoni district only). In general, households that utilized more technologies showed improved agricultural production and either improvements or at least no negative impacts in the other domains.

3.10. Wider scaling of SI technologies

In its second phase (2017–2021) Africa RISING set a target of reaching 0.7 million households with the project-validated SI technologies. Over the past 5 years (2017, 2018, 2019, 2020, and 2021), the project has managed to reach and benefit, through its validated SI technologies, nearly 0.4 million households (Figure 4). The Africa RISING project reached and benefited farmers with its validated SI technologies through direct researchers' engagement, development partnerships, and spillover scaling models/approaches.

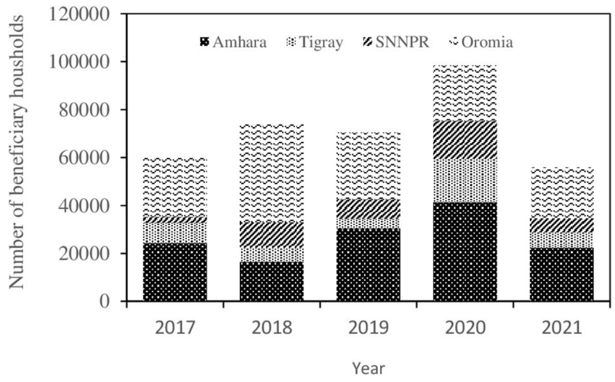

FIGURE 4
Beneficiaries of farm households from feed and forage interventions from 2017 to 2021 in the Ethiopian highlands.

4. Discussion/lessons

4.1. System orientations

A system is defined as a set of interrelated components working together for a common goal (Carlsson et al., 2002). It includes human and non-human actors, their market and non-market relationships, and the functional attributes of the actors and their relationships. A technological innovation system includes the various functions that must be performed by multiple institutional and economic structures to generate and disseminate a technology (Markard and Truffer, 2008). The system orientation of IAR4D requires that problems and solutions need to be co-investigated. Hence, joint learning through collaborative analyses of situations, collective action, and subsequent reflection are peculiar characteristics of IAR4D (Schut et al., 2016). IAR4D recognizes and engages actors and institutions at multiple levels of a technology's value chain (Nyikahadzoi et al., 2012; Adekunle and Fatunbi, 2014; Lunt et al., 2018).

Africa RISING farmers adopted and implemented different innovations based on their interests, capacities, and priorities. A systematic understanding of the interactions, synergies, and tradeoffs of the innovations at the farm/household level and beyond is useful for a complete evaluation of innovations. Research on interactions, synergies, and tradeoffs of the innovations implemented by each of the Africa RISING farmers requires skill and time. It also requires a willingness on the part of the CGIAR centers and local partners to jointly develop protocols and generate research evidence. The CGIAR centers are structured around commodity research foci such as dryland crops, root crops, livestock, water, trees, and natural resource management (NRM). This commodity focus is sometimes a challenge to bring them all together and study integrated innovations that would address interlinked system constraints. The Africa RISING project has considered landscape management as one of the core approaches to integrate crop-livestock-natural resource management and interlinked interventions.

4.2. Targeting/matching technologies

The capacities, preferences, and priorities of farmers to adopt agricultural technologies vary across and within regions, sites, and villages. External factors such as climate, edaphic conditions, policies, and institutions also matter in determining what type of technologies to adopt, when, where, and how much or how many of them to adopt. In this regard, working with typology groups was found useful. A typology groups the farms into relatively similar clusters. This can help to identify suitable farms to target innovations, allow tailoring of technologies to best-fit farm types (niches), scale up the effects of innovations, select farms to work within projects, scale-out innovations, explain trends and farmer "behavior," and verify the impact of interventions for different farm types (Alvare et al., 2014). Targeting or matching technologies to the different farm types speeds up technology uptake and paves the way for impact. The Africa RISING experience in the Ethiopian Highlands shows the possibilities of constructing farm types (farm typologies) in two ways, namely, ex-ante vs. ex-post, depending on circumstances. For instance, the shortage of protein-rich animal feed was the farmers' priority problem in the Ethiopian Highlands. Several farmers in the Africa RISING operational areas planted fodder trees such as tree lucerne (*Chamaecytisus palmensis*) and used them as supplementary feed for dairy cows and small ruminants. To facilitate further scaling of tree lucerne, we clustered farmers after the implementation of the fodder tree intervention and identified three major farm types along with their adoption characteristics for this technology. The farm types include resource-rich, middle-class, and resource-poor households (Mekonnen et al., 2017).

4.3. Technology adoption

The involvement of multiple actors with differentiated capacities and interests requires that IAR4D projects develop the capacities of all involved and develop effective communication and knowledge management systems. Notably, capacity gaps need to be defined by each actor, and capacity building needs to be executed with the right expertise (Nyikahadzoi et al., 2012; Adekunle et al., 2013). During capacity building, it is also necessary to consider developing capacities to work together in partnership and use innovation platforms for a transformational common good (ISPC 2016). Realizing the benefits of integrating SI interventions at the household scale has been a mantra for Africa RISING projects during its first phase. In practice, we have learned that the integration of SI interventions does not happen concurrently. Farmers prefer to test one or two technologies at a time to assess their workability and the benefits that they derive from them. Once they become confident with a limited number of technologies, they often proceed further down the intensification pathway by adopting further complementary interventions. This stepwise approach to SI appears to be the reality for many farmers. Our experience also taught us the importance of understanding the types of capacity building (practical training and demonstration) that the local communities need to navigate around blockages and speed up the wider scaling of innovations.

4.4. Farmers' innovation

The Africa RISING action research approach enhanced farmers' capacities to test and modify technologies according to their needs and circumstances. For example, the project introduced and demonstrated a livestock feed trough technology prototype in different sites. This feed-trough technology enabled farmers to reduce feed wastage and labor demand for feeding by over 30 and 20%, respectively. Farmers at the different project sites modified the feed trough technology in several ways. Some farmers constructed two sides (one side for cows and the other side for sheep/calves), and others constructed only one side (for cows or sheep). Some used iron sheets for shading, and others constructed the feed trough under trees. Some farmers who own more livestock constructed large feed troughs, while those with few livestock constructed feed troughs that can feed 2–4 livestock species. In another example, Africa RISING farmers in the SNNP region learned to graft avocados to increase their access to improved avocado varieties introduced by the project. All these examples show farmers' innovativeness and the need to tap into this potential in research for development practices.

4.5. Partnerships

Partnerships are key to bringing about the desired impacts. Africa RISING has been working with CGIAR centers, local universities, federal and regional research institutions, NGOs, private entrepreneurs, government extension, and farmers since 2012. All these institutions have their own working styles/approaches, priorities, and financial requirements. It is sometimes challenging to harmonize the conflicting interests of all the partners and bring them on board to achieve plans and targets. Partners' engagement in monthly meetings, planning and review meetings, annual learning events, field days, cross-site visits, and other capacity-building schemes fosters partnership, narrows communication gaps and helps to build strong relationships and create positive working environments. Our IPs and other structures for multi-stakeholder engagement have played an important role in making our partnerships successful (Lema et al., 2021). Some local decision-makers in the Africa RISING operational areas have continued using the innovation platform to periodically meet and discuss the development agendas for their respective districts and zones.

4.6. Wider scaling of SI innovations

Wider scaling of Africa RISING-validated technologies became evident through the creation of development partnership approaches. The Africa RISING project identified potential development partners that can allocate resources and time to widely scale SI innovations and benefit smallholder farmers. Government extension is a major development partner that has been widely scaling Africa RISING project validated SI innovations. The extension system can pick up validated

SI innovations and be widely scaled to many areas as the innovations align with their priority areas and development strategies. The Africa RISING project organized different capacity development events to familiarize the development partners with the SI innovations. However, capacity development alone would not be sufficient for the development partners to widely scale innovations. Backstopping development partners with some financial resources to purchase inaccessible inputs such as seeds/planting material for some improved forage and crop varieties is necessary to continue the wider scaling efforts (Gebreyes et al., 2021). It is important to see what limits the scaling of innovations to a large number of farmers, prioritize the gaps, and address them in a way that does not create dependency.

5. Conclusion

The first and second phases of the Africa RISING project in the Ethiopian Highlands explicitly used the IAR4D approach to guide their work. The approach used the four pillars to guide the process of translating the global Feed the Future initiative into locally relevant and usable research. As a result, several positive results were achieved. Africa RISING technologies were used as a basis for regional-level benchmarks in crop production because of their outstanding performance. Farmers who participated in community seed multiplication were able to sustain their production. Moreover, communities that were able to produce enough for their families and generate more income changed the attitude of farmers and encouraged them to produce improved animal forage, identify soil-specific fertilizer blends and rates for wheat production and reduce soil loss through integrated soil and water conservation practices. The research for the development experience also generated some key lessons. First, in system research, where farmers may be provided with a package of technologies, they tend to adopt them incrementally, with each step adding more value to their farm enterprise. It was also observed that farmers transition from being mere adopters of technologies to co-generators and innovators. Second, while joint assessment of problems is essential, the Africa RISING experience showed the need to take this one step further and conduct a joint assessment in clusters based on farmer typology assessment. This helps to better target technological solutions. Third, partnership in IAR4D requires the management of complex partnerships with strong facilitation skills needed to meet the various interests of different actors in innovation platforms. Fourth, broader scaling of SI technologies reaches and benefits smallholder farmers better through development partnership approaches. Finally, there is a need for strong documentation skills as capturing success stories and failures get complicated with time.

Data availability statement

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

Author contributions

The first draft of the manuscript was written by KM, MG, JH, and PT. Edited and reviewed by MB, SK, LT, GA, RY, AG, MT, KS, AA, and AW. 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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EDITED BY
Patrick Meyfroidt,
Universitécatholique de Louvain, Belgium

REVIEWED BY
Gideon Danso-Abbeam,
University for Development Studies, Ghana
Burarat Phesatcha,
Rajamangala University of Technology Isan, Thailand
Michiel M. Scholtz,
Animal Production Institute (ARC-SA), South Africa

*CORRESPONDENCE
Sirak Bahta
✉ s.bahta@cgiar.org

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Productive efficiency of beef cattle production in Botswana: a latent class stochastic meta-frontier analysis

Sirak Bahta[1]*, Omphile Temoso[2], John N. Ng'ombe[3], Karl M. Rich[4], Derek Baker[5], Simeon Kaitibie[6] and Patrick Malope[7]

[1]International Livestock Research Institute (ILRI), Nairobi, Kenya, [2]UNE Business School, University of New England, Armidale, Australia University of New England, Armidale, NSW, Australia, [3]Department of Agribusiness, Applied Economics, and Agriscience Education, North Carolina A&T State University, Greensboro, NC, United States, [4]Department of Agricultural Economics, Oklahoma State University, Stillwater, OK, United States, [5]UNE Centre for Agribusiness, University of New England, Armidale, Australia University of New England, Armidale, NSW, Australia, [6]Department of Agribusiness and Markets, Lincoln University, Christchurch, New Zealand, [7]Department of Agricultural and Applied Economics, Botswana University of Agriculture and Natural Resources (BUAN), Gaborone, Botswana

Introduction: Efficiency in food production is crucial for sustainable agriculture in developing countries. This paper contributes to the existing literature by presenting an innovative approach to modeling productive efficiency in beef cattle production. Treating farm performance across regions as unobserved heterogeneity, we determine technical efficiency of beef cattle production in Botswana. We aim to shed light on the factors influencing efficiency in this sector.

Methods: The study utilized block-level data from various annual agricultural surveys (2006–2014) covering 26 agricultural districts and six agro-ecological regions in Botswana. We employed a latent class stochastic frontier model complemented with the stochastic meta-frontier analysis.

Results: Results show that the best performing farming systems in terms of efficiency are districts with well-developed infrastructure and better access to output and input markets. In contrast, the farming systems that perform poorly consist of agricultural districts without access to livestock advisory centers, with higher average temperatures and foot and mouth disease, limiting access to export markets. The mean technical efficiency scores for beef production for agricultural districts in class one and two were 62 and 59%, respectively, implying high potential to improve beef production using the same level of agricultural inputs through efficiency-enhancing investments.

Discussion: Based on our results, it is crucial for agricultural policies to prioritize regionally specific investments that address the needs of the under-performing districts. By targeting the lagging districts, policymakers can help beef producers improve their input efficiency and bridge the technological gaps to the meta-frontier. This can be achieved through investments in infrastructure, access to livestock advisory services, and disease control measures. Such efforts will not only enhance the efficiency of beef production but also contribute to the overall sustainability of the agricultural sector in Botswana.

KEYWORDS

latent class stochastic frontiers, stochastic meta-frontier analysis, technical efficiency, Botswana, beef cattle production

1. Introduction

With the goal of improving the productive efficiency of beef cattle production in developing countries and advancing the way efficiency can be modeled in empirical research, we present a latent class (finite mixture) stochastic meta-frontier analysis of beef cattle production in Botswana. Our objective is to examine technological heterogeneity and technical efficiency differences amongst beef cattle producing districts over time in the context of a developing country. Botswana is one of the few sub-Saharan African (SSA) countries that export beef to high-value markets such as the European Union. Livestock production plays a vital role in the rural economy and development of the country as a source of food, income, employment, and investment opportunities for most rural dwellers (van Engelen et al., 2013; Statistics Botswana, 2015). In 2019, the livestock sector contributed about 45% of the value-added in the agricultural sector while agriculture contributed 2.1% of the economy's value added (Statistics Botswana, 2022). In addition, beef is the only contributor to foreign exchange earnings from the livestock sector. Therefore, understanding Botswana's technical efficiency of the beef cattle production systems and its drivers could be vital to the future orientation of Botswana's and similar countries' livestock industries, rural economies, and associated policy targeting.

Considering the above, this paper makes the following contribution to the literature. We exploit the observed heterogeneity of beef farms to identify technologies endogenously, measure their efficiency, and determine their sources and drivers. We adopt a latent class model (LCM) that combines a stochastic frontier approach (SFA) with a latent class structure. Unlike the approach used by previous researchers on a similar subject (e.g., Bahta et al., 2015; Temoso et al., 2015b), whereby a precise *prior* classification of farms is not made, farms are clustered according to differences in production technology. In fact, previous studies used farm management data bases which may not capture well the observable characteristics of farm (Besstremyannaya, 2011). Thus, our motivation to using a latent class stochastic frontier analysis stems from the fact that a LCM simultaneously identifies potentially unobservable technological differences and measures technical efficiency thereby providing management aspects that distinguish the most efficient location from the least efficient location.

While the use of the latent class stochastic frontier model (LCSFM) has proven useful in studying selected agricultural sectors, e.g., dairy farms (Alvarez and del Corral, 2010; Alvarez et al., 2012; Orea et al., 2015); and crops (Baráth and Fertő, 2015), its empirical application to the beef cattle sector is, to date, limited to a few studies (Martinez-Cillero et al., 2019; Dakpo et al., 2021). Martinez-Cillero et al. (2019) used the approach to evaluate the technical efficiency and technological heterogeneity of Irish beef farms, whilst Dakpo et al. (2021) measured the productivity of intensive and extensive grazing livestock farming systems in France. All these studies have concluded that if unobserved technology heterogeneity is not accounted for to model technical efficiency, results may be biased and the policy implications from those studies would be misleading. We build on this literature by applying the LCSFM methods to the beef sector in Botswana to provide an empirical evidence basis to inform policy design for Botswana and other developing countries whose beef sectors are their economic and social development mainstay.

The livestock sector in developing countries is an excellent example where efficiency of livestock production is under-researched despite being an important agricultural sector that contributes considerably to their economies. Apart from being under-researched, a few studies that estimate the technical efficiency of livestock production systems generally assume farms operate under a homogeneous technology. However, as shown by previous studies (e.g., Alvarez and del Corral, 2010; Alvarez et al., 2012; Baráth and Fertő, 2015; Orea et al., 2015; Martinez-Cillero et al., 2019; Dakpo et al., 2021), assuming homogenous technology may lead to unreliable technical efficiency, productivity estimates, and policy recommendations.

Moreover, technical efficiency analysis of beef cattle production matters because agricultural policy in most countries like Botswana favors the livestock sector, especially beef, at the expense of crop production (Bahta and Malope, 2014; Temoso et al., 2015a). Botswana's previous government initiatives include the Livestock Management and Infrastructure Development (LIMID) program, which promotes food security through improved productivity of cattle, small stock, and poultry [Ministry of Agriculture (MoA), 2010]; and the International Livestock Research Institute's (ILRI) project.[1] The ILRI project identified factors affecting the productivity of smallholder livestock farms and assessed their competitiveness and conditions for market participation and value addition (Bahta et al., 2013). International support to Botswana's livestock sector includes international development agencies (e.g., The World Bank, 2016) and international development researchers (e.g., ILRI, the Australian Centre for International Agricultural Research). However, despite receiving key public policy support, most of the funds and human resources allocated to the livestock sector are directed mainly to monitoring disease outbreaks, conducting vaccination campaigns, and implementing the traceability system (LITS)[2] (Bahta and Malope, 2014; Bahta et al., 2015). The remaining funds are spent on management advances that might boost productivity, such as improving input quality and allocation, technology adoption, training, and enhancing production efficiency and market access (Sigwele and Orlowski, 2015; Temoso et al., 2018).

Notwithstanding these efforts, scientific evidence suggests that the productive performance of beef cattle farms in developing countries (e.g., Botswana, Ghana, Kenya, and Zambia) is declining, with negative consequences on income and gross domestic products (Temoso et al., 2015b, 2018; Manyeki, 2020; Ankrah and Jiang, 2021; Odubote, 2022). For example, in Botswana, over the previous years, both off-take and birth rates remained below 10% except in 2013 and 2014, when the birth rate rose to 12.9 and 12.4%, respectively (Statistics Botswana, 2019). These findings suggest that there is potential to improve the performance of beef cattle in the traditional sector by scaling up both birth rates and off-take rates and reducing mortality rates. Beef productivity has been affected by various factors: recurring droughts; endemic animal diseases; biological inefficiencies (low birth rates and high mortality rates); inefficient operation of farms; slow adoption of improved breeding; and ineffective feeding approaches in the Botswana environment (van Engelen et al., 2013; Bahta and Baker, 2015; Temoso et al., 2015b; Statistics Botswana, 2019).

Scaling-up beef farmers' performance may require identifying the unobserved technological differences between regions to fully effective policy targeting. Therefore, as part of our contribution to the literature, we build on the LCSFM framework by estimating a stochastic meta-frontier (SMF) production function that encompasses all class frontiers (covering regions) to account for potential inter-class variation in

1 Competitive smallholder livestock in Botswana-http://surl.li/ajclx.

2 The LITS and disease control programs are both for export markets 'access, particularly the European Union (EU) (Bahta et al., 2015).

technology gaps in beef production. Instead of applying the LCSFM in conjunction with a deterministic meta-frontier as in Mekonnen et al. (2015), we adopt Huang et al.'s (2014) approach in the second stage whereby technology gap ratios are specified as a function of exogenous variables to account for group-specific environmental heterogeneity. While Mekonnen et al. (2015)'s study is close to ours, despite their novelty, Mekonnen et al.'s semi-parametric approach did not report any statistical properties of their meta-frontier estimates. A SMF approach mitigates this (Huang et al., 2014; Le et al., 2018). In particular, the SMF approach has an advantage over the deterministic meta-frontier approach in that its estimation uses a maximum likelihood function rather than mathematical programming and therefore is more suitable to separate potential random shocks from the technology gaps. Moreover, Mekonnen et al.'s (2015) study focuses on innovation systems in Africa while ours focuses on beef production systems in Botswana.

2. Literature review

Several researchers have proposed methods that deal with technological heterogeneity (Battese et al., 2004; Greene, 2005; Kumbhakar et al., 2009). In the case of observed heterogeneity, the most commonly used approach has two stages. The first stage involves splitting the sample into groups based on *prior* information about farms and specific exogenous characteristics. In the second stage, different production functions are estimated for each group (e.g., see, Battese et al., 2004; Newman and Matthews, 2006). One such approach is the SFA-based meta-frontier, which has been applied in the dairy industry (Moreira and Bravo-Ureta, 2010) and in a few cases to beef production (e.g., Otieno et al., 2014; Bahta et al., 2015; Temoso et al., 2015b, 2016). Otieno et al. (2014) classified beef cattle farms in Kenya into three production systems (nomadic pastoralism, agro-pastoralism, and ranches). Bahta et al. (2015) delineated three farm types while Temoso et al. (2016) and De Ridder and Wagenaar (1984) considered two farm types of production systems. Further, Temoso et al. (2015b) defined different production technologies based on their location in agro-ecological regions. A typology based on communal versus freehold livestock farms was used in Barnes et al. (2008) and Mahabile et al. (2002).

While it is essential that these studies have examined the performance of Botswana's livestock given the growing policy support, using partial measures of productivity (Abel, 1997; Behnke, 1985) has the limitation that input–output relationships are not attributed to either technologies or management. Analyses using more complete estimates of productivity that assume homogeneous production systems amongst farms have the limitation that productivity changes are associated with technology (Mahabile et al., 2002; Barnes et al., 2008). We are aware of only three studies (i.e., Bahta, 2014; Temoso et al., 2015b, 2016) that have measured the productivity of Botswana's livestock production systems while accounting for technological differences amongst systems. Bahta et al. (2015) applied a deterministic meta-frontier approach to cross-sectional data from three major livestock producing districts (i.e., South East, Chobe, and Central). Three types of beef production systems were recognized, namely *cattle only*, *cattle and crops,* and *mixed farms*. Results featured a tendency for efficiency to be positively related to production system diversity. Farm system makeup is clearly associated with technology. Temoso et al. (2015b) adopted a similar approach to panel data from 26 agricultural districts representing all six agro-ecological regions in Botswana. Their study found that prevailing environmental conditions and economic development in a given region influence productivity and the production technologies employed. Temoso et al. (2016) measured the productivity gap between traditional and commercial beef production systems and found significantly different productivity and deployment of production technologies between the two systems.

Similarly, Melo-Becerra and Orozco-Gallo (2017) assessed the efficiency of crop and livestock production systems in Colombia. Considering the different production systems with regard to climate, geography, and soil types, Melo-Becerra and Orozco-Gallo (2017) built on previous research by using stochastic meta-frontier techniques. They found that farmers in some production systems were benefiting from better production conditions due to the available natural resources, climate, and more favorable socio-economic conditions.

The methods used by the papers discussed above have received some criticism. First, if the *prior* classification is not precise, the first stage is likely to generate errors, which will deliver biased and inefficient estimates of the technological parameters in the second stage (Kumbhakar et al., 2009). Another practical limitation of the two-stage approach is that researchers usually must consider a specific exogenous characteristic to divide the sample and estimate the separate frontiers. This is likely to lead to an incomplete division of the sample because firms included in separate groups may share some features (Alvarez and del Corral, 2010; Martinez-Cillero et al., 2019). Also, this essentially mirrors criticism of the use of technological indicators, as outlined above, as such groupings may be both arbitrary and incomplete.

A recommended approach to account for potential unobserved heterogeneity is one that searches for a finite number of structures (or "classes") within the data (Alvarez et al., 2012). The latent class stochastic frontier model (LCSFM), sometimes referred to as a mixture of models, offers these facilities. In LCSFM, each firm or geographic location (district, country, region, etc.) can be assigned to a group using the estimated probabilities of possessing certain characteristics (separating variables) that are proxies for different technologies or production systems (Sauer and Paul, 2013). The LCSFM is suited to our empirical setting because livestock production in Botswana operates within a complex system (Bahta and Malope, 2014; Temoso et al., 2016), and the variation amongst farms may reflect a range of features such as breeds and genetics, soils and vegetation, land tenure systems, feeding systems, and disparities in the rate of uptake of new technologies.

Moreover, LCSFM is applicable where the researcher does not know *ex-ante* which farms belong to which particular production technology, nor the number of different technologies that exist in the sample (Mekonnen et al., 2015; Martinez-Cillero et al., 2019). Using panel data, this study extends the productivity analysis literature by combining the LCSFM with a stochastic meta-frontier analysis (in lieu of the deterministic meta-frontier). This is based on our conjecture that a stochastic meta-frontier envelops all the unobserved class frontiers thereby allowing us to account for potential inter-class variation in technology gaps, on an equally important sector for the global south – livestock production.

3. Materials and methods

3.1. Data and study area

We utilized block-level data from various annual agricultural surveys (2006–2014) covering 26 agricultural districts and six agro-ecological regions. A block is a smallest geographical area unit defined by Statistics Botswana and form the building blocks for larger regions. The annual agricultural surveys are collected through a stratified sampling framework. According to Statistics Botswana (2018, p. 15), independent sample sizes were estimated for each individual block and added to give the total sample size at the agricultural district level, agricultural region level, and national level. In this study, 259 blocks within the traditional/communal beef cattle sector over a nine-year period (i.e., a total sample size of 2050) were used for analysis. This is a larger sample size than previous livestock studies in Botswana that have used aggregated data at district and regional levels (e.g., Temoso et al., 2016).

We focus on the traditional beef cattle production system because the majority (78%) of farmers and cattle population (78%) in Botswana fall under this system, and it contributes the largest share of output to the livestock sector (Statistics Botswana, 2018). In addition, the recent agricultural surveys (since 2012) focus on collecting data for the traditional sector while the commercial sector coverage has been low and as such the recent commercial farms data cannot be used to produce meaningful results to guide policy and decision making (Statistics Botswana, 2019).

3.2. Descriptive statistics

Table 1 provides the definition, units, and summary measures of the production function variables, at the primary sample unit (PSU) level, that are used to explain technical inefficiency. For estimation, the dependent variable is beef output expressed in monetary value. Due to measurement difficulties, this study follows the revenue approach recently applied in the literature (Hong et al., 2019; Nguyen et al., 2021; Temoso et al., 2023) and defines output as:

$$Q_{i(j)} = \frac{\sum_{T}^{R} yp}{t} \quad (1)$$

where $Q_{i(j)}$ is the annual value of beef cattle output of the i^{th} farm in the j^{th} production system (measured in Botswana Pula[3]); R denotes any of the three forms of cattle output considered, i.e., current stock, sales or uses for other purposes in the past 12-month period; y is the number of beef cattle equivalents; p is the current price of existing stock or average price for cattle sold/used during the past 12 months; and t is the average maturity period for beef cattle in Botswana which, based on expert consultation, is assumed to be 4 years. Similarly, to ensure that the study captures the approximate share of feeds from different sources, the quantities of purchased and non-purchased (on-farm) feeds were first adjusted in accordance with the average annual number of dry and wet months,[4] respectively, in the country.

TABLE 1 Descriptive statistics of weighted production function variables and inefficiency effects at the block level.

Production function variable	Mean	Standard deviation
Total value of beef cattle output (Pula)	177,960	308,996
Feed cost (Pula)	2,142	7,178
Veterinary costs (Pula)	10,226	15,200
Labor cost (Pula)	3,750	12,339
Arable land area (hectares)	1.6	1.65
Annual precipitation (mm)	427	221.79
Inefficiency variables		
Average age of household head (Years)	53	7.85
Households with primary education (%)	56	21.92
Training (%)	7.0	10.4
Gender (% of men head of Households)	59.4	22.7
Artificial insemination (%)	1.34	4.25
Proportion of exotic breed (%)	22.0	4.92
Mortality rate (%)	7.04	5.17
Transport facility (% of households owning a truck)	6.0	9.21
Herd size	10,952	12,939
Households with crop income (%)	40.0	27.9
Gross off-take rate (%)	4.4	2.89
Industry-specific environmental variables		
Access to livestock advisory centres (LACs) (%)	81.6	38.8
Average temperature (degrees Celsius)	21.93	0.72

*, **, ***, indicate statistically significant at 10%, 5%, and 1% significance level, respectively.

Average feed prices were computed using the survey's price information collected for purchased feed with further validation by animal nutrition experts in the Department of Agricultural Research (DAR). Both purchased and non-purchased (the value of the latter is zero since no own grown feed is recorded in the database) feeds were then converted to improved feed equivalents by multiplying the respective feed quantities by the ratio of their prices (or shadow prices) to the average per-unit price of improved fodder. Thus, following Otieno et al. (2011) and Bahta et al. (2015), the total annual improved feed equivalent was computed as:

$$\left\{\varphi\left(p_f * d\right) + S\left(n_p * w\right)\right\} \quad (2)$$

where; φ and S denote, respectively, the ratio of prices of purchased and non-purchased feed to that of improved fodder; p_f and n_p represent the average quantities of purchased and non-purchased feeds, respectively, in kilograms per month; d is the approximate number of dry months (when purchased feeds are mainly used), while w is the length of the wet season (when farmers mostly use on-farm or non-purchased feeds) in a particular area. The other input variables included in the first stage of the model are land, labor, herd size, and average annual precipitation. Except for precipitation, the sample weight is used to obtain a weighted value for the other variables in the production function.

3 One Botswana Pula is on average 0.083 USD (Yahoo Finance 2022).

4 Botswana is an arid country and according to expert information the length of the wet season when farmers mostly use on-farm or non-purchased feeds do not exceed 5months. Consequently, the study uses 5 wet and 7 dry months, respectively.

As shown in Table 1, the average total value of beef cattle output is BWP 177,960. On the input side, the average land size – measured in terms of arable land in hectares – is 1.6 ha. Access to grazing land varies from communal lands where most smallholders graze their cattle freely to fenced lands, with an average land size per PSU of about 25 ha. The average total cost of labor per PSU is BWP 3,750. Agricultural labor measures the total labor cost, including permanent and temporary labor costs. Another key input variable is herd size, which reflects the stock size and is measured in beef cattle equivalents (Otieno et al., 2012; Bahta et al., 2015). We also included farm household veterinary costs. The average veterinary cost per PSU is BWP 10,226. The variable annual rainfall or precipitation is included to account for geographic variation and averages 427 mm.

The proportion of *exotic breeds*[5] may indicate adoption rates of advanced breeds and their impact on productivity (Temoso et al., 2016). The effect on productivity of the exotic breeds (both the Zebu/indicus and taurus) could especially be on crossbreeding and improving the Tswana breed in terms of weight of an animal which is one of the most important criteria in beef production. *Gross off-take rates*[6] refer to the ratio of livestock sold to the total number purchased and home slaughtered, whereby low off-take rates are associated with poor management and lack of marketing facilities (Temoso et al., 2016). *The mortality rate* is the ratio of the total number of deaths to the total number of livestock during the survey year. It is expected that farms with lower mortality rates are using better technologies and managing their livestock farms well and are likely to attain better productivity (Temoso et al., 2016).

The last rows in Table 1 contain descriptive statistics for the industry-specific environmental variables considered in this study. As mentioned before, industry-specific environmental variables go into the inefficiency term of the SMF model. Here, we consider access to livestock advisory centers (LAC) and mean temperatures recorded in all blocks within agricultural districts in Botswana during the period of analysis. The LACs are centers that provide livestock services required to help control and prevent livestock diseases. Access to LACs is important in Botswana as it provides animal health services through the sale of drugs, vaccines, and animal equipment as well as offering advisory services to farmers about animal health (Malope et al., 2016). However, access to LACs in Botswana is heterogeneous as some districts have more than one LAC center while others do not and this affects the livestock industry. Temoso et al. (2023) found that LACs affect Botswana's livestock's total factor productivity and its growth suggesting that access to LACs is appropriate to be considered an industry-specific environmental variable. In this study, access to LACs has the value of zero for blocks whose farmers had zero access to LACs and equals 1 for blocks whose farmers had access to at least one LAC. As for mean temperatures, Neibergs et al. (2018) suggest that temperature affects the growth of forage and timing of forage availability for grazing, which ultimately impacts stocking rates, turn-out dates for beef cattle. Thus, temperature may have important implications on the beef cattle production's meta-frontier, especially that it may not be homogeneous across all blocks within districts in Botswana. Because of the broadness of access to LACs and mean yearly temperatures, we consider these variables as industry-specific environmental variables in stage two of our SMF estimations.

3.3. Latent class stochastic production frontier

Following Orea et al. (2015) and Mekonnen et al. (2015), we specify a production function from the LCSFM as follows:

$$y_{it} = \alpha_{|j} + x_{it}\beta_{|j} + v_{it|j} - u_{it|j}, \tag{3}$$

where i represents blocks, t indicates time, and $j = 1,\ldots, J$ stands for class: we assume that the blocks within agricultural districts being analyzed operate an unknown finite number of different technologies which underlie the sample data. The dependent variable, y_{it} is a measure of a block's output, x_{it} represent a vector of input variables, $v_{it|j}$ is a noise term that follows a normal distribution with zero mean and class-specific constant variance, and $u_{it|j}$ is a class-specific one-sided error that captures the blocks' inefficiency (geometrically, the distance between the observation and the production frontier) and is assumed to follow a one-sided distribution (half-normal in this study). The two error components are assumed to be independent of each other.

The associated likelihood function conditional on class j for a block i at time t is given by:

$$LF_{itj} = \frac{\Phi\left(-\lambda_{|j} * \varepsilon_{it|j} / \sigma_{|j}\right)}{\Phi} \frac{1}{\sigma_{|j}} \phi\left(\frac{\varepsilon_{it|j}}{\sigma_{|j}}\right) \tag{4}$$

where $\varepsilon_{it|j} = y_{it} - \alpha_{|j} - x_{it}\beta_{|j}$, $\sigma_{|j} = \left(\sigma^2_{u|j} + \sigma^2_{v|j}\right)^{1/2}$, $\lambda_{|j} = \frac{\sigma^2_{uj}}{\sigma^2_{vj}}$

and ϕ and Φ represent the standard normal density and cumulative distribution functions (Greene, 2005). Then, the overall contribution of the block i to the conditional likelihood is:

$$LF_{ij} = \prod_{t=1}^{T} LF_{itj}. \tag{5}$$

The unconditional likelihood for block i is obtained as a weighted sum of its likelihood function across j class, where the weights (P_{ij}) are the probabilities of class membership, or:

$$LF_i\left(\theta,\delta\right) = \sum_{j=1}^{J} LF_{ij}\left(\theta_j\right) * P_{ij}\left(\delta_j\right), \text{ where } 0 \le P_{ij} \le 1, \text{and } \sum_{j=1}^{J} P_{ij} = 1 \tag{6}$$

Then, the logarithm of the overall likelihood function $LF_i\left(\theta,\delta\right)$ can be obtained as the sum of the individual likelihood functions $LF_{ij}\left(\theta_j\right)$, where θ_j represent the frontier specific parameters to be estimated:

5 The data from statistics Botswana aggregates all improved breeds as exotic breeds, hence not possible to evaluate the variation in terms of performance among different exotic breeds.

6 Gross off-take is calculated following Negassa and Jabbar (2008) as Gross Commercial offtake rate=Sales 0.5 (Opening stock+Ending stock)*100.

$$lnLF_i(\theta,\delta) = \sum_{n=1}^{N} \ln\left\{\sum_{j=1}^{J} LF_{ij}(\theta_j) * P_{ij}(\delta_j)\right\} \quad (7)$$

The prior class probabilities $P_{ij}(\delta_j)$ are parameterized as a multinomial logit model, to ensure that $0 \le P_{ij} \le 1$, and $\sum_{j=1}^{J} P_{ij} = 1$ such that:

$$P_{ij}(\delta_j) = \frac{\exp(\delta'_{|i} q_i)}{\sum_{j=1}^{J} \exp(\delta'_{|i} q_i)}, j = 1, \ldots, J, \quad (8)$$

where q_i represents the vector of block-specific but time-invariant variables that separate the blocks within the agricultural districts into different classes, and $\delta'_{|i}$ s the vector associated with parameters to be estimated (Mekonnen et al., 2015).

Maximizing the overall likelihood function specified in Equation 7 provides asymptotically efficient estimates of all parameters. It should be noted that unlike the two-stage procedures discussed above, LCSFM allows for all the observations in the sample to be used to estimate the underlying technology for each class (Martinez-Cillero et al., 2019). Each block within an agricultural district belongs to one and only one class, which implies that the probabilities of class membership in LCSFM merely reflect the uncertainty that researchers have about the true parameter (Orea et al., 2015). The estimated parameters in Equation 7 can be used to compute the posterior probabilities of class membership using the following expression:

$$P(j|i) = \frac{LF_{ij}(\theta_j) P_{ij}(\delta_j)}{\sum_{j=1}^{J} LF_{ij}(\theta_j) * P_{ij}(\delta_j)} \quad (9)$$

The probability in Equation 9 is then used to allocate each block to the class with its highest posterior probability. Alvarez et al. (2006) noted that Equation 9 is time-invariant, implying that each block within the agricultural district is modelled in the same group over time is the posterior probability for a given block i to belong to technology class J. It depends on prior parameters of class membership δ_j and the estimated parameters of the production function (θ, λ, σ). Following Mekonnen et al. (2015), we apply Schwarz Bayesian Information Criterion (SBIC) and Akaike Information Criterion (AIC) to our data in order to determine the number of classes. BIC and AIC can be computed as follows:

$$SBIC(j) = -2logLF(j) + \mathrm{K}\log(N) \quad (10)$$

$$AIC(j) = -2logLF(j) + 2K \quad (11)$$

where log $LF(j)$ represents the log-likelihood function of the model with j classes, N is the number of observations, and K represents the number of parameters to be estimated. After the j production frontiers have been defined, the technical efficiency of a block i in the t^{th} period for class-j production frontier can be estimated using the following equation:

$$TE_{it|j} = \exp(-u_{it|j}) = \exp(-E(u_{it|j} + v_{it|j}) \quad (12)$$

3.4. Stochastic meta-frontier estimation

One of the contributions of this study is, for the first time, to determine and compare the technical efficiency of beef cattle production across all the blocks and agricultural districts in Botswana. However, the efficiency score estimates across classes from Equation 12 are not directly comparable due to their either constituting different frontiers or different weights within frontiers. Following Mekonnen et al. (2015), this can be resolved by estimating a meta-frontier that incorporates all the class frontiers and facilitates efficiency comparison across all the blocks in all technology classes. A meta-frontier production function uses either panel or cross-sectional data to measure efficiency and production technological gaps (Battese and Rao, 2002; Battese et al., 2004), and the estimates of meta-frontiers are commonly used to compare relative efficiency scores of different classes or groups (Temoso et al., 2016).

Since its introduction by Ruttan (1971), several developments have led to two main ways in which a meta-frontier production function is estimated: a deterministic meta-frontier (O'Donnell et al., 2008) and a stochastic meta-frontier frontier (Huang et al., 2014). O'Donnell et al. (2008) deterministic meta-frontier is estimated by mathematical programming techniques which do not account for idiosyncratic shocks, and thus results are prone to random noise (Huang et al., 2014; Chang et al., 2015). To address this, Huang et al. (2014) proposed a stochastic meta-frontier (SMF) model that, rather than using mathematical programming techniques, uses econometrics to estimate meta-frontier parameters and account for random noise in the second stage. Because of this advantage, it is no surprise that several studies (e.g., Huang et al., 2015; Li et al., 2017; Melo-Becerra and Orozco-Gallo, 2017; Ng'ombe, 2017; Alem et al., 2019; Obianefo et al., 2021 among others) have used a SMF model. A SMF approach requires specifying technology gap ratios (TGRs) as a function of exogenous environmental variables and has desirable statistical properties for inference (Huang et al., 2014). Thus, in the second stage, this study builds on previous latent class frontier research (e.g., Mekonnen et al., 2015; Orea et al., 2015) by estimating a SMF to incorporate all the class frontiers to facilitate efficiency comparison of all the blocks within the agricultural districts in all technology classes in Botswana.

Following Huang et al. (2014), a meta-frontier production function that would underlie all latent class frontiers in the t^{th} period is $f_t^M(X_{jit}), j = 1, 2, \ldots, J$ where j denotes classes. By definition, $f_t^M(X_{jit})$ is the meta-frontier that envelopes individual class frontiers: $f_t^j(X_{jit})$. Their relationship is

$$f_t^t(X_{jit}) = f_t^M(X_{jit}) e^{-U_{jit}^M}, \forall j, i, t \quad (13)$$

where $U_{jit}^M \ge 0$, which means $f_t^M(.) \ge f_t^j(.)$ and that the ratio of the jth class's production frontier to the meta-frontier is the technology gap ratio (TGR) expressed in Equation 14:

$$TGR_{it}^{j} = \frac{f_t^j\left(X_{jit}\right)}{f_t^M\left(X_{jit}\right)} = e^{-U_{jit}^M} \leq 1. \tag{14}$$

Based on Equation 14, a TGR value that equals one implies that the most advanced technology to produce outputs was employed. A TGR value of less than one implies that an economic unit of interest failed to adopt the most advanced technology, perhaps due to economic and/or environmental conditions (Huang et al., 2014; Ng'ombe, 2017). Therefore, Huang et al. (2014) consider that the technology gap component of U_{jit}^M is group-, block-, and time-specific and that it would depend on the adoption of the meta-frontier production technology available. Given any input level X_{jit}, a meta-frontier $f_t^M\left(X_{jit}\right)$ and a block's observed output y_{jit} can be decomposed into three components as

$$\frac{f_t^j\left(X_{jit}\right)}{f_t^M\left(X_{jit}\right)} = TGR_{it}^j \times TE_{it}^j \times e^{V_{jit}} \tag{15}$$

The three components are, respectively, the *i*th block's TGR_{it}^j, technical efficiency, and random noise $e^{V_{jit}}$. While it is well known that TGR_{it}^j and TE_{it}^j lie between 0 and 1, the meta-frontier does not necessarily envelope all economic agents' observed outputs due to random noise. It is the unrestricted fraction in Equation 15 that differentiates modeling a meta-frontier by stochastic frontier analysis (SFA) from using data envelopment analysis (DEA). To account for random noise, Equation 15 can be rewritten as

$$MTE_{jit} \equiv \frac{f_t^j\left(X_{jit}\right)}{f_t^M\left(X_{jit}\right)e^{V_{jit}}} = TGR_{it}^j \times TE_{it}^j \tag{16}$$

where MTE_{jit} is a block's technical efficiency with respect to the meta-frontier production technology, $f_t^M\left(X_{jit}\right)$ instead of *j*th latent class's production technology. In terms of estimation, mathematical programming techniques would minimize the sum of squared deviations between $f_t^M(.)$ and $\hat{f}_t^M\left(X_{jit}\right)$ and the standard errors associated with meta-frontier parameter estimates would be obtained by bootstrapping and or simulation methods (Ng'ombe, 2017). But under Huang et al.'s (2014) approach, for estimation purposes, Equation 13 is re-specified as

$$\ln f_t^j\left(X_{jit}\right) = \ln f_t^M\left(X_{jit}\right) - U_{jit}^M \tag{17}$$

The class-specific frontier $f_t^j\left(X_{jit}\right)$ is not observable, but its estimates are from the first step. In this study, it is from LCSFM. Since the fitted values of $f_t^j\left(X_{jit}\right)$ (i.e., $\hat{f}_t^j\left(X_{jit}\right)$ and true frontier values $f_t^j\left(X_{jit}\right)$ are different, Equation 17 becomes

$$\ln \hat{f}_t^j\left(X_{jit}\right) = \ln f_t^M\left(X_{jit}\right) - U_{jit}^M + V_{jit}^M \tag{18}$$

where V_{jit}^M is the statistical noise to characterize the deviation of $\hat{f}_t^j\left(X_{jit}\right)$ from $\ln f_t^j\left(X_{jit}\right)$. This can be shown as

$$\ln \hat{f}_t^j\left(X_{jit}\right) = \ln f_t^M\left(X_{jit}\right) + V_{jit}^M \tag{19}$$

Equation 18 looks like the common stochastic frontier regression model and is therefore referred to as the SMF model. Following Huang et al. (2014), since $\ln f_t^j\left(X_{jit}\right)$ can be obtained by maximum likelihood estimation, its estimates are consistent and asymptotically normally distributed. The error V_{jit}^M is assumed to be distributed as $N\left(0,\sigma_v^{M2}\right)$ while $U_{jit}^M \geq 0$ is assumed to be distributed as $U_{jit} \sim N^+\left(\mu^j\left(Z_{jit}\right),\sigma^{j2}\right)$, where Z_{jit} are now group-specific environmental variables. Huang et al.'s (2014) method allow for the estimated latent-specific frontier to be greater than or equal to the meta-frontier due to the error V_{jit}^M in Equation 18. But by construction, the meta-frontier is always higher than the true latent class-specific frontier, i.e., $f_t^M\left(X_{jit}\right) \geq f_t^t\left(X_{jit}\right)$(Huang et al., 2014). The estimated TGR becomes

$$\hat{TGR}_{it}^j = \hat{E}\left(e^{-U_{jit}^M} \mid \hat{\varepsilon}_{jit}^M\right) \leq 1 \tag{20}$$

where $\hat{\varepsilon}_{jit}^M = \ln \hat{f}_t^j\left(X_{jit}\right) - \ln \hat{f}_t^M\left(X_{jit}\right)$ which is the estimated residual of Equation 16. In sum, we use the LCM frontier analysis in the first step and SMF approach in the second step because the latter allows the presence of V_{jit}^M leading to the estimated TGR in Equation 20 not being influenced by random shocks, unlike the deterministic programming method (Huang et al., 2014).

3.5. Empirical model

In the efficiency literature, there are generally two functional forms used to specify the production function: the Cobb Douglas function and translog function. In this study, the translog function is assumed for the production function, which has sufficient parameters to provide a second-order approximation (Coelli et al., 2005). Unlike the Cobb Douglas production function, the translog production function does not impose prior restrictions on the production technology and can handle a large number of inputs and treat them interactively. However, the flexibility of translog function comes at a cost – there are more parameters to estimate, and this may give rise to econometric difficulties such as multicollinearity (Coelli et al., 2005) as well as failure to satisfy its basic theoretical restrictions (i.e., positivity, linear homogeneity, curvature, and monotonicity). However, the translog functional form remains the most widely used form in literature (Serletis and Feng, 2015). Our specification of the translog production function is:

$$\ln y_{it} = \beta_k\big|_j \ln X_{itk} + \frac{1}{2}\sum_{k=1}^{K}\sum_{g=1}^{G}\beta_{gk}\big|_j \ln X_{itk}\ln X_{itg} + \delta_t\big|_i t + \gamma_t\big|_i t^2 + v_{it} - u_{it}\big|_j \tag{21}$$

where the β's and δ's are parameters to be estimated and *k* is the *k*th group or block. Whilst subscript *i* denotes the blocks within the agricultural district, t is the linear trend that accounts for neutral technical change, j denotes the different classes to be estimated, and whilst y and x are the logarithms of beef output and a vector of inputs, respectively. For consistency, we also assumed the translog functional form for the SMF model. As with the distribution of the inefficiency term, for consistency, a half-normal distribution is also assumed in the second step.

Estimation proceeded as follows. In the first stage, we estimated the LCSFM from which class j's fitted value of output for the ith block in period t were pooled. Here technical efficiency scores associated with each class were estimated. In the second stage, we used the pooled fitted values from stage one for each class to estimate Equation 16. As mentioned before, we used access to LACs and the mean temperature per year in degrees Celsius that Botswana recorded during the period of analysis. Notice that following Wang and Schmidt (2002), Ng'ombe and Kalinda (2015), and Yu and Jaenicke (2020), the frontier and inefficiency part of the model in both first and second stage were estimated simultaneously to detour from inconsistency that comes with the two-stage approach whereby the frontier and inefficiency functions are estimated separately.

4. Results and discussion

4.1. Latent class stochastic production frontier estimates

In this study, we determine the number of classes into which the blocks within the agricultural districts could be classified, using the Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC) (Orea and Kumbhakar, 2004; Alvarez and del Corral, 2010). The AIC was relatively the lowest for LCSFM with two classes, thus implying that it is the preferred model over the LCSFM with three classes. Table 2 presents the maximum likelihood estimates for the parameters in the stochastic production frontier. All estimated first-order parameters in the LCSFM fall between zero and one in both classes and the pooled frontier, thus satisfying a monotonicity condition that all marginal products are positive and diminishing at the mean inputs (with the exception of veterinary expenditure in Class 2).

The elasticity of output with respect to labor and arable land are both positive and statistically significant for both classes and larger than for any other input. A possible explanation for this could be that farmers who have more arable land are more likely to have more crop residues that they can use to supplement their animals and thus reduce feed costs (Bahta and Baker, 2015). Veterinary expenditure was significant for Class 2 and the pooled model but not for Class 1. Across classes (and the pooled model), the livestock feed variable was not significant. In general, our analysis shows that variables related to labor and inputs show more significance in the Class 2 model. Arable land and labor are more significant in the Class 1 model. This suggests a more intensive oriented production system in Class 1 than Class 2. The pooled model demonstrates a broader pattern of significance, but the two class models depart from it substantially, which suggests that the underlying technologies are different both from the pooled model and from each other.

4.2. Determinants of productivity among smallholder beef producers in Botswana

Determinants of technical inefficiency are presented in Table 3: a negative coefficient indicates that the variable has a positive effect on TE. The table shows that all candidate determinants of technical efficiency are negative and statistically significant for the pooled model (except artificial insemination and mortality rate variables). In Class 1, all variables (except transport facility and crop income variables) were significant. However, in Class 2, a smaller set of variables [gender, exotic breed, cattle population (herd size), crop income, and gross off-take rates] were significant.

The coefficients for education and training are negative and significant for the pooled model and Class 1, from which we infer that blocks/agricultural districts with relatively more farmers with some formal schooling or having received agricultural training tend to be technically efficient. This may be due to farmers with more education responding more readily by adopting new technologies (Temoso et al., 2023). These results are consistent with Bahta and Malope (2014), who found a positive relationship between education and productive efficiency amongst the smallholder beef farmers in Botswana but contradicts Otieno et al. (2014), who found that smallholder farmers with formal education and higher income in Kenya, were relatively less efficient. The coefficient of gender is negative and statistically significant. Male farmers may generally be more efficient than female farmers in beef production possibly due to more access to resources, greater exposure to, and experience of livestock management in Botswana.

In both classes, we found a negative and significant coefficient of the use of exotic breeds, which indicates that the higher the proportion of exotic breeds, the more efficient the agricultural district. These results show that having fewer indigenous cattle breeds and more crossbreeds are likely to lead to higher beef production efficiency. Crossbreeds between exotic and indigenous cattle have the potential to improve productivity and their suitability to the adverse production environments compared to the indigenous breeds. Wollny (2003) points out that controlled cattle breeding could increase efficiency through the improvement of genetic quality, enhancing the adaptation of cattle to environmental conditions, and ensuring an optimum stocking rate to feed supply within and between years.

Herd size (cattle population) has a negative and significant effect, which implies farmers owning larger herds are more technically efficient than those owning small herds. The direction of the effects is consistent with *a priori* expectations. The results suggest that there is scope to increase productive efficiency by increasing herd size. However, such a strategy would need to be done with consideration of other factors such as the availability of suitable grazing and water, and local environmental conditions, the management in place in communal grazing areas.

The coefficient of crop income is negative and statistically significant for the pooled sample and Class 1, which implies earning income from crop production improves the technical efficiency of farmers. As observed by Bahta and Malope (2014, p. 415), "the results suggest that income from crop farming is being reinvested into livestock farming, and/or that there are other synergies between the two farm activities including the use of crop residues as feed resources."

TABLE 2 Production models for beef production in Botswana, 2006–2014.

	Pooled (n=2050)		Class 1 (n=985)		Class 2 (n=1,065)	
Independent variables	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Constant|	11.15***	0.155	11.61***	0.242	10.01***	0.211
LN_LABOR	0.644***	0.099	0.428**	0.194	0.560***	0.189
LN_VETERINARY	0.760***	0.138	0.220	0.211	1.160***	0.235
LN_ARABLE LAND	0.430***	0.112	0.511***	0.147	0.434**	0.187
LN_FEED	0.080**	0.037	0.018	0.050	0.074	0.060
LN_PRECIPITATION	0.095	0.284	−0.041	0.437	0.125	0.478
LAB_VET	−0.003	0.034	0.061	0.047	−0.054	0.068
LAB_LND	−0.067*	0.039	−0.084	0.055	−0.039	0.083
LAB_FEE	0.016	0.010	0.003	0.020	0.035	0.022
LAB_PRECIP	−0.021	0.095	0.031	0.192	−0.046	0.187
1/2LAB_SQ	−0.204***	0.040	−0.114*	0.064	−0.139	0.089
VET_LAND	0.049	0.051	−0.025	0.067	0.155	0.107
VET_FEED	−0.042***	0.014	0.004	0.022	−0.073***	0.028
VET_PRECIP	0.128	0.111	0.227	0.172	−0.158	0.227
1/2VET_SQ	−0.217**	0.095	−0.079	0.121	−0.295*	0.173
LND_FEE	0.012	0.013	−0.014	0.020	0.022	0.027
LND_PRECIP	−0.053	0.078	−0.036	0.124	0.115	0.134
1/2LND_SQ	−0.153**	0.064	−0.110	0.096	−0.290**	0.127
FEE_PRECIP	0.003	0.030	−0.043	0.043	0.044	0.056
1/2FEE_SQ2	0.006	0.011	0.02828*	0.016	−0.001	0.019
1/2PREC_SQ2	−0.119	0.349	0.118	0.536	−0.218	0.646
TIME	−0.039	0.026	−0.048	0.045	−0.016	0.042
TIMESQ	0.003	0.003	0.005	0.005	0.001	0.004
Lambda|	6.177***	0.027	0.99681***	0.000	0.962***	0.006
Sigma(u)|	3.55	7.67	77.63	134,953	7.762	495.86

*, **, ***, indicate statistically significant at 10%, 5%, and 1% significance level, respectively.

TABLE 3 Determinants of productivity among smallholder beef producers in Botswana.

Latent class stochastic frontiers						
	Pooled (n = 2,050)		Class 1 (n = 985)		Class 2 (n = 1,065)	
Independent variables	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Age	−0.136	0.100	−0.404**	0.202	0.025	0.359
Education	−0.120***	0.038	−0.167**	0.083	−0.139	0.092
Training|	−0.004***	0.001	−0.005***	0.002	−0.006	0.004
Gender	−0.184***	0.032	−0.152*	0.082	−0.2784***	0.096
Artificial insemination	0.0003	0.001	0.003*	0.001	−0.002	0.002
Exotic breed	−0.0803***	0.007	−0.081***	0.021	−0.160***	0.028
Mortality rate	0.019	0.012	−0.042*	0.024	−0.007	0.036
Transport facility	−0.0023**	0.001	0.001	0.002	−0.005	0.004
Herd size	−0.0748***	0.006	−1.253***	0.122	−0.0539***	0.012
Crop income	−0.0329***	0.008	0.017	0.017	−0.067***	0.023
Gross off take	−0.0953***	0.020	−0.136***	0.046	−0.202***	0.049

*, **, ***, indicate statistically significant at 10%, 5%, and 1% significance level, respectively.

The coefficient for the availability of transport is negative and significant only for the pooled model, which implies that having access to a transport facility has the potential to improve production efficiency. These results imply that those farmers with access to transport facilities can conveniently access distant markets in search of better sale prices for their output and also access key inputs such as veterinary medicine and supplementary feeds. This effect appears to be generally applicable to all cattle farms but is not reflected as specific to either of the two classes.

The coefficient of gross off-take rate (the ratio of livestock sold to the total number purchased and home slaughtered) is negative, indicating efficiency gains from an increase in gross off-take rates. Temoso et al. (2016) found similar results for traditional farmers and argued that they are due to farmers' selling their animals to meet their immediate cash needs and during drought seasons as a drought risk management strategy.

Moreover, Table 4 presents the parameter estimates of the SMF model. All of the coefficients of the individual inputs are positive and significantly different from zero and imply that, on average, an extra unit of each of these inputs positively affects the technology gap ratios (TGRs) of beef production in Botswana. When they enter the production function as squared values of their original form, most of the inputs (except) feed have negative and statistically significant coefficients. However, when used interactively, some of the inputs affect TGRs of beef production positively or negatively to highlight heterogeneous effects of inputs on how far districts in each class may be off the country's stochastic meta-frontier.

With regard to industry-specific environmental variables, average temperature and access to LACs are significantly different from zero at 1 and 5% significance levels, respectively. The negative coefficient on access to LACs implies that districts whose beef cattle farmers have access to LACs operate closer to the meta-frontier production function than those that do not have access to LACs. This is plausible because, through LACs, such services as the purchase of drugs, vaccines, animal equipment, and animal health advice are available to an agricultural district (Malope et al., 2016) and enabling such areas to operate near the frontier. On the other hand, we find that an increase in average temperature would result in a district operating far from its beef cattle production frontier. In sum, findings from industry-specific environmental variables imply that higher temperatures would result in the district's technology at beef cattle production being inferior. However, districts whose farmers have access to LACs operate with superior technology to those without.

TABLE 4 Stochastic-meta frontier parameter estimates.

Variable name	Coefficient	Std. Error
Constant	10.170***	0.042
LN_LABOR	0.652***	0.019
LN_VETERINARY	0.660***	0.035
LN_ARABLE LAND	0.530***	0.020
LN_FEED	0.079***	0.007
LN_PRECIPITATION	0.097*	0.051
LAB_VET	−0.003	0.008
LAB_LND	−0.083***	0.007
LAB_FEE	0.005**	0.002
LAB_PRECIP	0.019	0.016
1/2LAB_SQ	−0.086***	0.004
VET_LAND	0.092***	0.010
VET_FEED	−0.039***	0.003
VET_PRECIP	0.049**	0.019
1/2VET_SQ	−0.122***	0.010
LND_FEE	0.010***	0.002
LND_PRECIP	0.013	0.015
1/2LND_SQ	−0.117***	0.006
FEE_PRECIP	0.007	0.005
1/2FEE_SQ	0.005***	0.001
1/2PREC_SQ	−0.087***	0.032
TIME	−0.005	0.005
TIMESQ	0.000	0.000
Industry-specific environmental variables		
Access to livestock advisory centres (LACs)	−0.479**	0.241
Average temperature	11.844***	1.990
Constant	−30.149***	4.524
Ancillary parameters		
SIGMA_U	0.112	0.110
SIGMA_V	0.100***	0.005
THETA	0.708***	0.015

4.3. Technical efficiency and technological gap analysis

Generally, the agricultural blocks in latent Class 1 are more technically efficient than those in latent Class 2. The mean technical efficiency scores for beef production between 2006 and 2014 for the blocks in Class 1 and Class 2 are 0.616 and 0.591, respectively. While the difference in mean technical efficiency scores is small, it is significantly different from zero at a 1% significance level as indicated by the *t* statistics in Table 5. These results imply that the blocks in Class 1 may be more homogenous (Mekonnen et al., 2015) and on the same path toward their frontier further than those in Class 2. In addition, these results imply that there is high potential in both blocks in Class 1 and Class 2 to increase beef production output by 38.4 and 40.9%, respectively, using the same amount of inputs. With regard to MTE, its mean values for districts in Classes 1 and 2 are, respectively, 0.563 and 0.528 and the mean difference between them is significantly different from zero. These mean scores imply that, on average, districts in Class 1 are significantly closer to the industry's beef production potential than their counterparts in Class 2. That is, beef producers in Class 2 would have to increase their production levels to close the gap with the industry's potential and their counterparts in Class 1.

Our results are not directly comparable to previous estimates from Bahta et al. (2015) and Temoso et al. (2016), which may have been overestimated if technology heterogeneity is present in the sample but not accounted for in the estimation process. Based on the highest posterior probability, the model classified 125 blocks as Class 1 and the remaining 136 blocks as Class 2. It is noted that some agricultural

TABLE 5 Mean difference between Class 1 and Class 2 efficiency measures.

Group	Observations	Mean	Std. Err.
TGR mean difference between Class 1 and 2			
Class 1	985	0.9187	0.0011
Class 2	1,065	0.8916	0.0021
Combined	2,050	0.9046	0.0013
diff = mean(1) − mean(2)	0.0271 (t = 11.0388)		
TE mean difference between Class 1 and 2			
Class 1	985	0.6156	0.0102
Class 2	1,065	0.5908	0.0071
Combined	2,050	0.6027	0.0061
diff = mean(1) − mean(2)	0.0248 (t = 2.0234)		
MTE mean difference between Class 1 and 2			
Class 1	985	0.5632	0.0092
Class 2	1,065	0.5280	0.0066
Combined	2,050	0.5450	0.0056
diff = mean(1) − mean(2)	0.0352 (t = 3.1351)		

districts have blocks that belong to either Class 1 or 2. Thus, a 50% frequency percentage was used as a cut point to classify the agricultural districts into either Class 1 or 2.[7] The minimum posterior probability of belonging into either class is 0, whereas the maximum is 1 and 0.99 for classes 1 and 2, respectively. For the agricultural districts which belong to Class 1, the average posterior probability of belonging to class one is 99.6%, whereas, for those that are categorized as Class 2, it is about 96%.

Figure 1 provides the average Beef Technical Efficiency (TE) Scores of Agricultural Districts in Botswana, 2006 to 2014 (the average technical efficiency scores of beef production for Classes 1 and 2 agricultural districts are also presented in Appendix 1.1). In Class 1, the top five performing agricultural districts are, respectively, Gantsi, Hukuntsi, Letlhakane, Tutume, and Selebi Phikwe districts, while the three lowest performers are Ngamiland west, Kweneng South, and Barolong, respectively.

These results possibly reflect livestock production specialization of those agricultural districts, where cattle production is the most dominant agricultural activity, followed by goats and sheep farming (Statistics Botswana, 2015). Moreover, these are the districts with a relatively large number of commercial farmers (e.g., Sandveld Ranches), so the results may indicate technology spillovers (i.e., adoption of better breeds and livestock management, etc.) from commercial farmers in those regions. For Class 2, the highest performers are Kweneng West and Bobonong, while the lowest performers are Kweneng South and Ngwaketse South (Figure 1 and Appendix 1.1).

7 Hukuntsi and Ngwaketse North agricultural districts are exceptions since an equal number of blocks belong to Class 1 and 2, a score of exactly 50/50 or a cut point of 50%. A decision to delineate these agricultural districts to either class 1 or 2 was made by comparing the average technical efficiency scores.

Figure 2 presents the technology gap ratio scores (TGR) and meta-technical efficiency (MTE) scores, which are estimated with respect to the stochastic meta-frontier (SMF) that encompasses all the class stochastic frontiers, thus allowing direct comparison of the efficiency of a given agricultural district to any other agricultural district in Botswana. The TGR measures the technological gap faced by an agricultural district in each class when their performance is compared against any agricultural district in the sample. A higher (lower) TGR implies a smaller (larger) technology gap between the class frontier and the meta-frontier. A value of 1 (100%) is equivalent to a point where the class frontier coincides with the meta-frontier.

According to Figure 2 and Appendix 1.2, on average, Class 1 agricultural districts have superior beef production technology to Class 2 agricultural districts. Amongst Class 1 agricultural districts, Kweneng South, Selebi Phikwe, Borolong, Sorrow, Letlhakane, Serowe, Tutume, Mahalapye West, Plapye, and Tutume have the highest beef farming technology (TGR of more than 0.9), whilst Gantsi and Hukuntsi have the least beef farming technology (TGR of 0.87). In Class 2, Mahalapye East, Kgatleng, Chobe, and Ngwaketse West have the highest beef production technology (TGR more than 0.9), whilst Tati and Tonota have the least (TGR of 0.81–0.84). Figure 2 and Appendix 1.3 also shows that the technical efficiency score relative to the meta-frontier (available beef production technology) for Class 1 is, on average, higher than for Class 2 (Appendix 1.4). Overall, the top-performing agricultural districts in Botswana are Letlhakane, Gantsi, and Hukuntsi. Whilst, Barolong, with higher TGR, recorded relatively lower meta technical efficiency. Although Barolong district was traditionally a mixed farming area, in recent times, arable agriculture has become the mainstay of the area's economy. This shift of farmers from beef cattle farming to arable agriculture may explain the lower performance of this district as compared to the other livestock specialization districts such as Gantsi and Hukuntsi.

4.4. Implication of technology differences between Class 1 and Class 2 districts

The previous section reveals the existence of clear significant differences in beef production technology between Class 1 and Class 2 agricultural districts. Table 5 below further illustrates this difference, with Class 1 districts significantly outperforming Class 2 districts in all efficiency estimates.

A major reason for the difference in beef production technology is resource endowment. Most parts of Botswana are disadvantaged by unfavorable environmental conditions, and the performance of different sectors within agriculture is closely related to these conditions (Burgess, 2006). For example, a descriptive analysis showed that the average temperature in Class 1 is 21.5 degrees Celsius while it is 22.3 degrees Celsius in Class 2, whose difference is statistically significant. Most importantly, and not coincidentally, our SMF model results indicated that higher temperature affects productive efficiency of the district, and the higher temperatures recorded in Class 2 adds to a long list of plausible reasons for inferior productive efficiency in Class 2. Class 1 districts are mainly composed of livestock specialized districts (e.g., Gantsi, Hukuntsi, Tsabong, Mahalapye West, and Letlhakane), whilst Class 2 is composed of agricultural districts suitable for crop production (e.g., Chobe, Mahalapye East, and Tati) (Burgess, 2006; van Engelen et al., 2013). In addition, the least performing agricultural

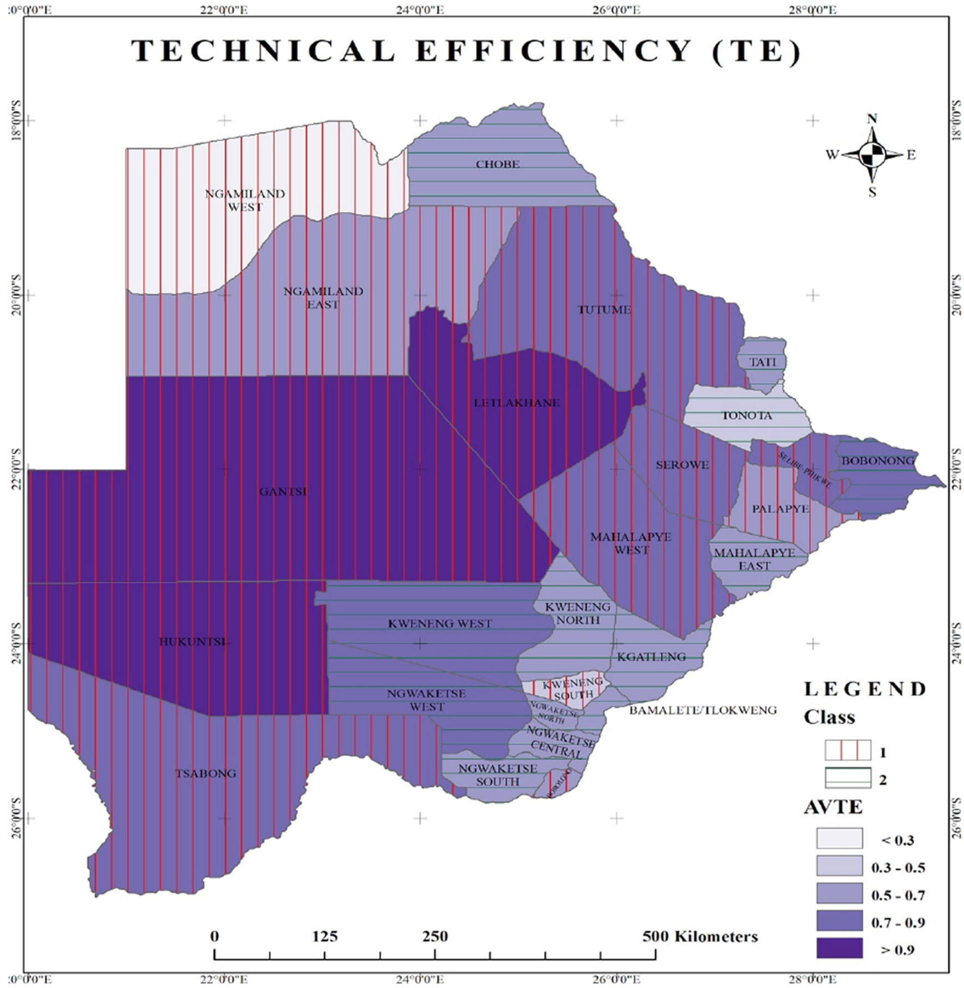

FIGURE 1
Average Beef Technical Efficiency (TE) Scores of Agricultural Districts in Botswana, 2006–2014.

Class 2 districts are located in wildlife areas, foot-and mouth disease (FMD)-endemic areas, and FMD-intensive surveillance zones.

Another reason for the difference in productivity is that the more productive agricultural districts tend to have large commercial farms that employ improved livestock farming practices. In addition, smallholder farmers operating in the vicinity of these large commercial farms benefit from technology spillovers from these commercial farms. These findings are consistent with evidence from Southern Africa (e.g., Thirtle et al., 1993; Temoso et al., 2016). Moreover, a simple descriptive analysis indicates that at least 91% of farmers located in Class 1 have access to livestock advisory centers (LACs), while only 72% have access to LACs. We found access to LACs to have the potential to improve beef cattle production efficiency is a plausible justification for this difference in efficiency statistics between the two classes.

Other more productive agricultural districts such as Selebi Phikwe, Palapye, and Tutume are located in the Eastern part of the country where Government of Botswana agricultural policies and investment in agricultural infrastructure have produced better road networks, access to markets and information, and proximity to extension services and the main export abattoirs in Francistown and Lobatse (Temoso et al., 2015a,b).

The implication of these results is that the best performing agricultural districts have either benefited from enabling government agricultural policies (e.g., access to LACs) or have the resources to develop, adapt and implement good livestock production practices. By virtue of their existence in FMD zones and unfavorable mean temperatures, the least performing agricultural districts may be deprived of enabling government livestock development policies. This situation can be reversed with the adoption of a commodity-based trade approach that allows greater integration of FMD-free with endemic zones (Rich and Perry, 2011; Naziri et al., 2015; Rich and Bennett, 2019).

These differences suggest the presence of clearly differentiated technologies among smallholder beef producers in Botswana and hence where policies to improve productivity could be focused. This study shows that providing livestock farmers with relevant livestock extension and better access to markets would facilitate better use of available technology by the majority of farmers, who currently produce sub-optimally. Possible essential interventions would include improving farmer access to LACs to help or speed up the provision of appropriate knowledge on animal husbandry, such as cattle feeding methods, disease monitoring, and breeding (Bahta et al., 2015). Chronic under-investment in the livestock sector is a significant

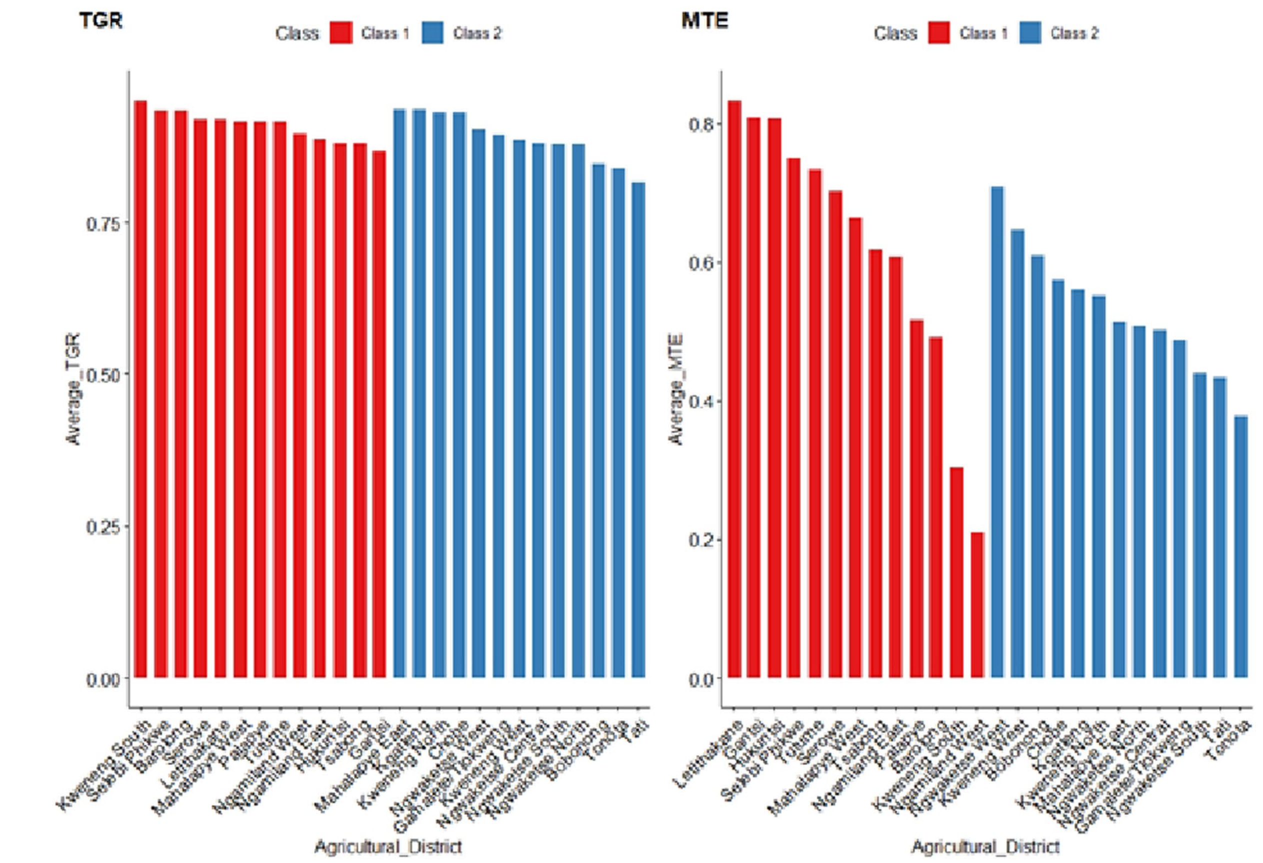

FIGURE 2
TGR and MTE Scores of Agricultural Districts in Botswana, 2006–2014.

constraint to the livestock sector. Therefore, it is crucial for the livestock stakeholders in Botswana, particularly the department of animal production, to make a case for sustainable livestock investments. The country needs to improve the evidence base by adopting livestock master plans, which provide crucial evidence that livestock ministers often lack regarding returns on investment (Bahta et al., 2020). Such evidence is essential to get financial resources for livestock development from ministries of finance, donors, as well as public and private investors.

5. Conclusion and policy implications

This study has employed a latent class stochastic frontier model (LCSFM) complemented with the stochastic meta-frontier (SMF) to identify different technology models for Botswana's beef production and then assessed production efficiency within those models. This advances on previous studies of efficiency, particularly for agriculture and developing countries, in that the technologies were not imposed *a priori* but rather emerged from the analysis.

We conclude that there are differences in technologies applied in Botswana's beef industry that led to differences in inefficiencies across agricultural districts. To our knowledge, we provide the first quantitative measures of these effects (TGR measures and average technical efficiency scores) applied to Botswana and to extensive livestock production systems. We find that the majority of Botswana's agricultural districts that perform better at beef cattle production are those located in areas where well-developed infrastructure and access to both output and input markets exist. Although unsurprising, this result's strong confirmation lends support to its advocacy on other subjects. The centrality of infrastructure and market access to production efficiency, valid across all technologies, supports calls for improvements in all production areas.

The demonstrated use of differentiated beef production technologies by agricultural districts lends support to the importance of correctly accounting for heterogeneity in order to make appropriate policy recommendations regarding beef production and performance. The results of the study indicate that amongst factors of production, the beef output is positively related to the availability of labor, the size of arable land areas, feed availability and herd size. These result advocates for the implementation of policies that promote ownership of arable land in which farmers can plant fodder and or other crops, from which they could use residues to feed their livestock.

Agricultural districts that were found to perform poorly in terms of efficiency are mostly those without access to LACs, higher mean temperatures as well as where there is an occurrence of foot and mouth disease, which limits access to the Botswana Meat Commission (BMC) abattoirs. These agricultural districts also have large herds of wildlife, which leads to conflicts between wildlife and livestock keepers as the wildlife kills their livestock, and, in some cases, there are carriers of the FMD virus. The implication of this is that better ways of minimizing conflicts between wildlife and livestock should be found in order to improve beef production efficiency.

The use of improved breeds (exotic and crossbreeds) was found to positively influence efficiency, and this result is valid across the technologies identified. Hence uptake and controlled cattle breeding practices should continue to be encouraged for all production systems, as it has the potential to improve efficiency through the improvement of genetic quality and to enhance adaptation of cattle to environmental conditions. Similarly, the study has also shown that beef production efficiency is positively associated with levels of formal education across all production systems, and hence policies that address education and training of smallholder farmers should be pursued.

We find that animal mortality is associated with reduced beef production efficiency. Offtake, although a contributor to efficiency, is also likely to indicate forced management procedures, perhaps as an alternative to mortality where sales are infeasible or carried out too late. These results also apply across the technology spectrum and advocate for improvement in animal husbandry, alongside better trading conditions and raised marketing skill levels with a focus on closing the technology investments in livestock development between the two classes.

Amongst substantial variation within the classes, the mean technical efficiency scores for Classes 1 and 2 are 62 and 59%, respectively. We infer that there is scope for improvement in production without using additional inputs. This study has provided insights into possible mechanisms for improving beef cattle production by identifying variation in efficiency statistics between districts while unearthing reasons for possible discrepancies between the localities and contexts. Several topics for future research are apparent, including the study of the detail of spillovers between production systems and the enhanced definition of outputs to include environmental products and contributions to sustainability.

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

SB contributed to conceptualization, investigation, data curation, resources, methodology, writing, editing, and review. OT contributed to conceptualization, investigation, methodology, editing, review, and supervision. JNN contributed to investigation, methodology, writing, editing, and review. KR, DB, SK, and PM contributed to conceptualization, investigation, methodology, writing, editing, and review. All authors read and approved the final manuscript.

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Conflict of interest

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

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Supplementary material

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EDITED BY
Folorunso Mathew Akinseye,
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Kenya

REVIEWED BY
Luciano Gebler,
Brazilian Agricultural Research Corporation (EMBRAPA), Brazil
Suhas P. Wani,
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India

*CORRESPONDENCE
Johnny Kofi Awoonor
✉ jkawoonor@csir.org.gh

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Soil suitability assessment for sustainable intensification of maize production in the humid Savannah of Ghana

Johnny Kofi Awoonor[1]*, Bright Fafali Dogbey[2] and Gabriel Willie Quansah[3]

[1]Soil Genesis, Survey and Classification Division, CSIR-Soil Research Institute, Kumasi, Ghana, [2]Department of Soil Resources Management, CSIR College of Science and Technology, Accra, Ghana, [3]Laboratory Analytical Services Division, CSIR-Soil Research Institute, Kumasi, Ghana

In sub-Saharan Africa (SSA), food security is a significant challenge due to unreliable rainfall and depleting soil fertility. Most of the soil resource in the sub-region which constitutes majority of the fields of smallholder farmers is degraded. Hence, there is a need to identify suitable soils for sustainable intensification. The objectives of this study were to: (i) evaluate the suitability and fertility constraints of soils and (ii) discuss the influence of soil properties on maize production in the Nkoranza (north and south) district. A total of sixty (60) soil samples were sampled from smallholder farms under careful consideration of topography and the spatial pattern of land use systems. The evaluation of soil suitability was carried out using climate (temperature and rainfall) and physico-chemical characteristics of soils for maize (*Zea mays*) production. The results indicated that soil texture varied from sandy loam to sandy clay loam. Soil organic carbon concentration (SOC) ranged between 0.55 and 2.02%. Total nitrogen (TN) and SOC were low in all soil types except in the *Bediesi series (Haplic Luvisol)*. Base cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) were low and varied between soil types. Although climatic factors and physical properties were highly suitable (S1), more than half of the pedons were moderately suitable (S2). The soils functioned at a moderate capacity for maize production. The major limitations identified were sub-optimal and related to soil fertility (CEC). Pearson correlation revealed a relationship between parametric actual index (PAI) and parametric potential index (PPI; $r = 0.940$, $p < 0.003$) and between soil resilience index (SRI; $r = 0.768$, $p < 0.037$) and the relationship between these variables is a perfect correlation. Soil management is required to increase maize yield in the study area. Soil erosion prevention measures such as cover crops, mulching, organic manure (poultry), and mineral fertilizer application are recommended to improve soil fertility in the Nkoranza (north and south) district. This study can inform policies and interventions geared toward sustainable agricultural intensification. Land and soil are heterogeneous and any decision on intensification in this study accounted for the prevailing local conditions of the study area. Therefore, indexing soil suitability using climate (rainfall and temperature), physical land characteristics (topography, drainage) and chemical properties (pH, SOM, SOC, TN, Av. P, Av. K, etc.) of soil resources for sustainable intensification of maize is proposed for smallholder farming communities of Nkoranza (north and south) districts in the Forest-Savannah Transition Zone of Ghana.

KEYWORDS

land suitability, soil fertility, sustainable intensification, soil resilience, maize, Ghana

1. Introduction

Agriculture is the backbone of African countries south of the Sahara Desert and employs more than 60% of its population (AGRA, 2014). Intensification of crop production, which is mainly based on rainfall has not matched population growth (Pradhan et al., 2015; Giller et al., 2021). Yields have stagnated over the past half century [Food and Agriculture Organization (FAO) of the United Nations, 2020a] rendering small farm owners financially poor to afford recommended inputs. According to Food and Agriculture Organization (FAO) of the United Nations (2020b), cereal production is low with an average yield of 1.6 t ha^{-1} compared to the global average of 3.9 t ha^{-1}. Also, the per capita income deficit for cereals increased from 1.5 million tons in 1967 to more than 20 million tons in 2015 (Sanchez, 2002; van Ittersum et al., 2016). These projections indicate that the sub-region requires about 35 million tons of cereal imports to satisfy the demands of the growing population [Food and Agriculture Organization (FAO) of the United Nations, 2015].

Sustainable supply of food, feed and fiber to a growing world population estimated at more than 9 billion by 2050 is a global concern (Foley et al., 2011; van Bussel et al., 2015). Therefore, the conservation of natural resources require an increase in yield on each hectare (Iizumi et al., 2018) of arable land suitable for intensification. Thus, increasing food production on existing farmlands is an important component of the sustainable intensification (SI) concept. Hence, the need to develop a robust indexing method to identify soils suitable for sustainable intensification (Claessens et al., 2013; Panel, 2013). This means intensifying food production and ensuring that the natural resources that sustain and improve agriculture for future generations are maintained and improved (Pretty and Bharucha, 2014). Sustainable intensification of agriculture paradigm was introduced by the British Royal Society of London (BRSL) in 2009 (Baulcombe et al., 2009). The BRSL defined SI as an agricultural production system that increases yield without adverse environmental impacts.

Maize importation is not economically feasible to eradicate food shortages. Sustainably intensifying the area under cultivation can increase domestic food production and this forms the basis for achieving Sustainable Development Goals #1 (zero poverty), #2 (zero hunger), #3 (enhance good health and wellbeing), #12 (responsible contribution and production), #13 (mitigate climate change), and #15 (sustenance of life on land, reduce soil degradation, and support biodiversity) (United Nations, 2016). Maize production is mostly subsistence, and most smallholder farmers use little or no soil amendments (Fening et al., 2005, 2009; Bationo et al., 2018). Nutrient depletion ranges from 40 to 60 kg of nitrogen (N), potassium (P) and phosphorous (K) ha yr^{-1} (AQUASTAT and FAO, 2005; Bationo et al., 2018), are among the highest in SSA. This is due to a decline in soil fertility as a result of continuous cropping without replenishment (Sanchez et al., 1997; Sanchez, 2002), as well as low and erratic rainfall are among biophysical constraints (International Center for Soil Fertility and Agricultural Development, 2007).

However, low maize yield is further attributed to the inability of farmers to apply even the blanket fertilizer recommendation [Ministry of Food and Agriculture (MoFA), 2011]. Also, the soil in the study area is depleted and does not meet the food demand of the growing population via area expansion-based crop production by small farm holders (Awoonor et al., 2021). Therefore, sustainable intensification is the only way for farmers to access high quality and affordable fertilizers that increase yield and profit for farmers in the rural communities. Also, intercropping is a form of a sustainable intensification cropping system that uses mutually beneficial ecological relationships that arise when two or more crops are cultivated, either as mixtures or in rotations (e.g., mixed cropping, rotations etc.). The low productivity from small farm holdings is due to biophysical factors related to declining soil fertility, pest and diseases, limited use of external input, unfavorable government policies, markets, institutional arrangements, as well as the effects of climate change in recent years. Much effort must be incorporated into soil management to ensure agricultural sustainability (Asiamah, 2008; Gelaw et al., 2015; Vanlauwe et al., 2015).

Farming activities are semi-intensive due to the peculiar nature of the native vegetation. The sustainability of an agricultural production system measures how the qualities of a land unit match the requirement of a particular form of land use [Food and Agriculture Organization (FAO) of the United Nations, 1976, 1985]. Some farming practices are not sustainable (Stoorvogel et al., 1993; Nandwa, 2001). These have resulted in environmental consequences, such as frequent changes in temperature, potential evapotranspiration, and changes in rainfall patterns with a pronounced decline throughout the transition zone. These challenges, if not addressed, will further reduce agricultural productivity, which adversely affects food security and rural livelihoods (Lal, 2006; Frelat et al., 2015). These challenges resulted in a relatively low annual yield despite the high potential for improvement. In spite of these challenges, an increase in organic matter can improve soil nutrients retention and release, improve soil water holding capacity, as well as control and reduce soil erosion on small farmlands. Several authors (Mbagwu et al., 1984; Lal, 1987, 1997) stressed that at the field and plot level, soil erosion can cause a yield reduction of about 30-90% in some shallow root-restrictive soils in the tropics and subtropics.

Land suitability assessment is conducted to manage soil resources sustainably to determine which type of soil resource is most suitable for a particular crop (Jones et al., 2013). The evaluation of land suitability involves identification and measurement of land quality and its assessment for alternative uses. The principles of land evaluation involve comparing the quality of land with the requirements of specific crops (Ranst et al., 1996; Ande, 2011). It involves the limiting factors of a particular crop for production [Food and Agriculture Organization (FAO) of the United Nations, 1976; Young, 1980]. The goal of this evaluation process is to increase productivity of soils for the specified crop. Crop suitability is a measure of the climatic and other biological properties of an area that sustains the production cycle of crops in order to meet current or expected targets. The farmer's challenge is often associated with or dependent on the suitability of soils for an intended purpose. The mismatch of crops with land use requirements has not ensured a reliable supply of food produced in the FSTZ. Therefore, soil suitability assessment identifies areas where adaptation measures are generally required to prevent the consequences of the climatic suitability of a crop.

In Ghana, maize is grown on small holdings by low-income farmers in rural communities. Hence, the need to evaluate the suitability of soils to increase maize production without depleting soil fertility. Climate and soil are the main environmental factors that determine crop yield. Furthermore, decreased soil fertility, increased soil erosion, erratic rainfall, emerging diseases, insect and pest infestations, and poor management of natural resources and land use have exposed the Nkoranza district (north and south) to food and nutrition insecurity. Additionally, land is becoming a scarce resource due to population growth. The associated economic pressures have exerted pressure on the limited natural resources available, resulting in a reduction in agricultural productivity per hectare.

According to Ogunkunle (1993, 2016) and Kihoro et al. (2013), the need to evaluate farmlands is because the soil classification system, with its maps and accompanying legends, does not meet the current needs and aspirations of most smallholder farmers and other land users. The impact of mismanagement of land resources and the lack of land utilization regarding land's potential suitability remain a challenge in developing countries such as Ghana. A more comprehensive land suitability evaluation for maize production was adopted, as suggested by Sys (1985). The need to identify the suitability of areas suitable for specific or selected crops improves the productivity and resilience of smallholder farms (Debesa et al., 2020).

Furthermore, limited attention has been paid to soil suitability assessment impacts on smallholder agricultural options for diversification of maize production systems in the study area. To the best of our knowledge, there are few publications that assess crop suitability at the national or local level to guide smallholder farmers select the most suitable crop for their farming communities to build resilience (Janzen et al., 2011). The adoption of appropriate land use management based on technological input enhance soil resilience. The use of proven scientific inputs (e.g., ISFM) results in a synergistic and positive effect on inherent soil properties, terrain, landscape and climatic factors (Lal, 1997). Again, the current food crisis after the COVID-19 pandemic has resulted in increased food prices. Hence, the need to feed an increasing population of 30 million in a changing world climate is a major challenge facing the government of Ghana.

Therefore, there is the need to identify suitable soils for sustainable intensification. The term suitable in this study refers to soils that support resource-efficient and cost-effective responses to agronomic interventions without physical, chemical, and biological degradation when subjected to intensification (Claessens et al., 2013). Intensification is producing more unit of output per units of all inputs and through new combinations of inputs and related innovations (Panel, 2013). Also, sustainable intensification involves improving the physical input-output relations to increase the overall efficiency of production. Thus, maize production on existing small-holder farms forms an important component of the sustainable intensification paradigm indicated by Claessens et al. (2013). This study assessed the importance of climate (temperature and rainfall) and soil (physical and chemical) properties on the suitability of land for maize production in smallholder farms in the study area. The main objectives were to assess the morphological, physical, and chemical properties of soils and their suitability for growing maize on sustainable bases in the Nkoranza (north and south) district of Ghana.

2. Materials and methods

2.1. Description of the study area

The study area falls within Ghana's Forest-Savannah Transition Zone (FSTZ). The geographic location lies between longitude 1° 10′ & 1° 55′ West and latitude 7° 20′ & 7° 55′ North, covering ∼2,592.09 km^2 (see Figure 1).

Soil moisture and temperature regime of Nkoranza's north and south districts is udic and hyperthermic (Wambeke, 1974). According to the Koppen-Geiger climate classification, the area experiences the tropical savannah climatic regime (Aw) (Peel et al., 2007). The study area has distinct climates (McSweeney et al., 2010). Annual rainfall, although high, varies between 1,200 and 1,600 mm year^{-1} (Table 1). Temperatures are high throughout the year (Kasei, 1993; AQUASTAT and FAO, 2005), with a mean monthly temperature range between 24 and 30°C (Dickson and Benneh, 1995). Annual potential evaporation is about 1400 mm and relative humidity varies from 90 to 95% in the rainy season to 75 to 80% in the dry season (Christiansen and Awadzi, 2008). The study area is a major producer of maize (Dickson and Benneh, 1995).

The FSTZ is characterized by deep, well-drained soils with sandy clay loam texture, strongly weathered, highly leached and acidic (pH: 5.1–6.5) (Adjei-Gyapong and Asiamah, 2002). These soils are easily eroded once the forest or savannah vegetation has been removed [Food and Agriculture Organization (FAO) of the United Nations, 2015, 2020a]. The soils contain a small amount of plant-available nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), with low cation exchange capacity (<10 cmol kg^{-1}). Drainage is related to topography. Poorly drained, flood-prone clay to loamy sand textured gleysols are found in valley bottoms (Annan-Afful et al., 2004, 2005; Owusu-Bennoah et al., 2008). Six (6) soil types (Table 1), namely: *Kpelesawgu* (Dystric Plinthosol), *Changnalili* (Gleyic Plinthosol), *Damongo* (Rhodic Luvisol), *Murugu* (Haplic Luvisol), *Bediesi* (Dystric Nitisol), and *Sutawa* (Thapto-Plinthic Luvisol) was identified and classified using the Ghana Interim Soil Classification System (GISCS) (Phillips and Wills, 1963; Adjei-Gyapong and Asiamah, 2002). The soils were reclassified using the FAO/WRB classification [IUSS Working Group (WRB), 2015]. Most of these soils were developed from hydrological conditions along slopes. These geomorphological processes resulted in different soils from uplands (north-west and south-west) to lowlands (north-east and south-east sections of the Nkoranza district), resulting in various formations of soil associations. *Bediesi-Sutawa* association was associated with upland soils, *Damongo-Murugu* was attributed to middle slope soils, while *Kpelesawgu-changnalili* association were ascribed to lowland soils (Adu and Mensah-Ansah, 1995; Agyili, 2003) Soils of the district are generally deep on the upper, middle, and lower slopes.

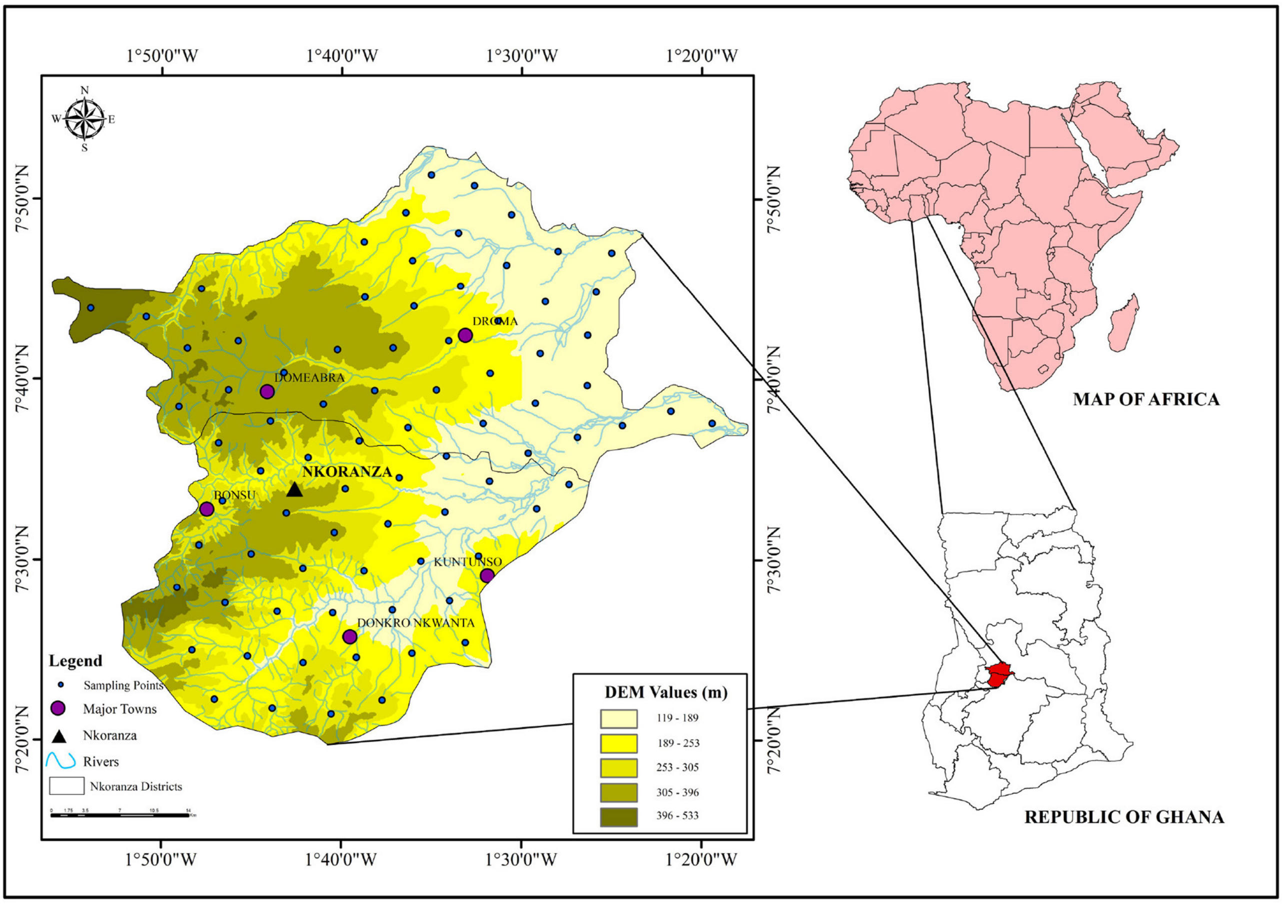

FIGURE 1
Illustrates the study area with soil sampling points.

2.2. Soil analysis

A systematic stratified sampling procedure was used to distribute sampling points throughout the study area under careful consideration of topography and the spatial pattern of smallholder land use systems. For morphological description of benchmark soils, soil pits (2 m L × 1.5 m W × 1 m D) were dug and described according to the recommendations of IUSS Working Group (WRB) (2022). Sixty (60) soil samples were collected at a depth of 0 – 20 cm, air-dried and passed through a 2-mm sieve. Soil color was determined using the Munsell Color Chart. Soil particle size (sand, silt, and clay) was determined with standard Bouyoucos hydrometer method (Bouyoucos, 1962). Bulk density (BD g cm^{-3}) was determined using the core method (Blake and Hartage, 1986). The soil reaction (pH) and electrical conductivity (EC) were measured in distilled water in a soil: water ratio of 1:2.5 w/v soil/water suspension (Olsen et al., 1982; Thomas et al., 1996; Rhoades, 2018). Total nitrogen (TN) was determined using the Kjeldahl method (Soil Survey Staff, 2006), available phosphorus (Av. P) determined colorimetrically after extraction with Bray's No.1 solution (Bray and Kurtz, 1945), available potassium (Av. K) by flame photometry (Motsara, 2015), and cation exchange capacity (CEC) was determined by ethylenediamine tetraacetic acid (EDTA) titrimetric method after extraction with 1 M ammonium acetate solution buffered at pH 7 (Thomas, 1983). Soil organic carbon (SOC) was determined with the Walkley and Black wet combustion method as described by Jackson (1973). Base saturation (BS) was determined as the ratio of basic cations in CEC.

2.3. Determination of soil suitability

In terms of agriculture, land suitability evaluates land to meet the agro-ecological requirements of a given crop to increase yield (Kawy and El-Magd, 2012). Land suitability assessment assesses relevant land characteristics such as soil, climate, and topography [Food and Agriculture Organization (FAO) of the United Nations, 1976; Young, 1980] to the requirements of a particular crop. These were regrouped into three thematic indicators. These indicators, as adopted from Baroudy (2016), and Diallo et al. (2016) are soil fertility, chemical, and physical quality indices (Equation 1):

$$LS = (FQI \times CQI \times PQI)^{1/3} \quad (1)$$

TABLE 1 Land qualities/characteristics (ranges) of soil series in the study area.

Soil series	Annual rainfall (mm)	Dry season (months)	Mean temp. (○C)	Relative humidity (%)	Slope (%)	Drainage	Soil depth (cm)	Coarse fragment	Soil texture
Bediesi	≥1,200	3	≥26.5	≥80	2–5	Good	> 221	Nil	SL
Sutawa	≥1,200	3	≥26.5	≥80	2–8	Moderate	> 155	Nil	SCL
Kpelesawgu	≥1,200	3	≥26.5	≥80	1–2	Moderate	> 98	Nil	SL
Changnalili	≥1,200	3	≥26.5	≥80	1–2	Poor	> 74	Nil	SL
Damongo	≥1,200	3	≥26.5	≥80	2–5	Good	> 183	Nil	LS
Murugu	≥1,200	3	≥26.5	≥80	4–8	Moderate	> 179	Nil	LS

SL, sandy loam; SCL, sandy clay loam; CL, clay loam; LS, loamy sand. Source: Modified from Sys et al. (1991).

The above equation was used to calculate land suitability for maize in the study area. From equation 1, *LS* is the land suitability factor, *FQI* is the soil fertility quality index, CQI is the soil chemical quality index, and *PQI* is the soil physical quality index. Soil fertility index (Equation 2) was calculated as:

$$FQI = (S_{SOC} \times S_{TN} \times S_{Av.\ P} \times S_K \times S_{CEC})^{1/5} \quad (2)$$

where S_{SOC}, S_{TN}, $S_{Av.P}$, S_K, and S_{CEC} are parameters that express factors for soil organic carbon, total nitrogen, phosphorus, potassium, and cation exchange capacity content. The chemical quality index was calculated using Equation 3;

$$CQI = (S_{Na} \times S_{pH} \times S_{EC})^{1/3} \quad (3)$$

where S_{Na}, S_{pH}, and S_{EC} are parameters that express factors for sodium, soil pH, and electrical conductivity. The physical quality index was calculated using Equation 4

$$PQI = (S_t \times S_s \times S_{cf} \times S_d \times S_w \times S_g)^{1/6} \quad (4)$$

where S_t, S_s, S_{cf}, S_d, S_w, and S_g are parameters that express factors for texture, structure, coarse fragment, depth, drainage, and slope (gradient). The parameters or factors for the evaluation process were rated (Sys, 1985; Sys et al., 1993). For this evaluation exercise, rates were assigned to the elements of each particular parameter with valid scores ranging from 0, the worst condition, to 100, rated as the best condition (Baroudy, 2016). For each class, a weighted index score was calculated according to the importance of its role in the land evaluation process. The suitability ratings were as follows: S1-highly suitable, S2-moderately suitable, S3-marginally suitable, and, N-unsuitable. The values of the final results were compared with two parametric methods, the square root and the Storie method (Storie et al., 1976).

For the non-parametric approach, soils were placed in suitability classes by matching these climatic characteristics (rainfall, temperature, humidity) with the agronomic requirements of the maize crop (chemical elements: SOC, TN, SOM, Av. P, Ex. K, etc.). An optimal soil property value for a crop must have no limitation. However, if the attribute is unfavorable to the crop, there is a limitation. These limitations range from 0 (no limitation) to 4 (very severe limitation). A value of 100 is assigned when the characteristics of the soil are optimal for the intended use. However, if the characteristic is not helpful, a low value is assigned, reflecting the degree of limitation for climate (c), topography (t), soil water conditions (w), soil physical characteristics (s) and soil chemical characteristics (f). The product of these parametric values gives the soil suitability index as described in Food and Agriculture Organization (FAO) of the United Nations (1976), Ogunkunle (1993). The Storie method was used in the calculation of the land index (I) (equation 5):

$$I = A \times \frac{B}{100} \times \frac{C}{100} \times \frac{D}{100} \quad (5)$$

where *I* is the suitability index. *A* is the rating of the surface texture parameter, and *B, C,* and *D* are the rating values for other parameters. A score ranging from 0 to 100% was determined for

TABLE 2 Land requirements suitability classes for maize (Sys et al., 1993).

Land qualities	Suitability classes					
	S1 (1) 100%	S1 (2) 95%	S2 85%	S3 60%	N1 40%	N2 25%
Climate (c)						
Annual rainfall (mm)	850–1,200	850–750	750–600	600–500	550–500	<300
Length of dry season (months)	<1	1–2	2–3	3–4	–	>4
Mean annual maximum temp. (○C)	24–26	26–32	32–35	35–40	–	>40
Average daily minimum temp. (○C)	17–18	18–24	24–28	28–30	–	>30
Mean annual temp. (○C)	24–26	26–32	32–35	35–40	–	>40
Relative humidity (%)	50–80	50–42	42–36	36–32	32–30	>30
Topography (t)						
Slope (%)	0–2	2–4	4–8	8–16	>16	>16
Wetness (w)						
Drainage	Good	Moderate	somewhat	Poor, aeric	Poor, but drainable	Poor, not drainable
Soil physical properties						
Structure	Blocky	Blocky	–	–	Massive	Massive, single grain
Coarse fragments (%)	0–3	3–15	15–35	35–55	–	>55
Depth (cm)	>100	75–100	50–75	30–50	20–30	<20
Fertility (f):						
CEC (cmol $_{(+)}$ kg^{-1})	>24	24–16	<16	<16	<10	<10
BS (%)	>80	80–50	50–35	35–20	<20	<20
pH (1:2.5)	6.6–6.2	6.2–5.8	5.8–5.5	5.5–5.2	<5.2	<5.2
TN (%)	> 0.2	0.15–0.2	0.1–0.15	< 0.1	–	–
Av. P (mg kg^{-1})	>25	>25	6–25	<6	–	–
SOC (0–20 cm) (%)	>1.5	0.8–1.2	0.6–0.8	0.5–0.6	<0.5	<0.5
Ex. Ca (cmol $_{(+)}$ kg^{-1})	10–15	5–10	1–5	<1	–	–
Ex. K (cmol $_{(+)}$ kg^{-1})	>0.2	0.1–0.2	<0.1	<0.1	–	–
Ex. Mg (cmol $_{(+)}$ kg^{-1})	2–5	1–2	<1	<1	–	–
Ex. Na (cmol $_{(+)}$ kg^{-1})	>0.5	0.40–0.5	0.2–0.34	<0.2	–	–
Salinity and alkalinity (*n*):						
EC (dS m^{-1})	0–2	2–4	4–6	6–8	8–12	>12
ESP in topsoil (%)	<6	<6	6–15	16–25	>25	–

CEC, cation exchange capacity; BS, base saturation; pH, soil hydrogen concentration; TN, total nitrogen; Av. P, available phosphorus; SOC, soil organic carbon; Ex. Ca., exchangeable calcium; Ex. K, exchangeable potassium; Ex. Mg, exchangeable magnesium; Ex. Na, exchangeable sodium; EC, electrical conductivity; ESP, exchangeable sodium percentage.
Source: Modified from Sys et al. (1991).

each factor and the scores were multiplied to generate an index rating (Storie et al., 1976). The square root method uses the formula (Equation 6):

$$I = R_{min}\sqrt{\frac{A}{100}} \times \sqrt{\frac{B}{100}} \times \sqrt{\frac{C}{100}} \times \sqrt{\frac{D}{100}} \quad (6)$$

where *I* is the square root index, R_{min} is the minimum rating, and *A, B, C,* and *D* are the remaining rating values (Khiddir, 1986).

The rating of each criterion is derived from field observation and laboratory analysis of each land characteristic, and the comparison of these measures with a specific crop (maize) requirement (Table 2). After rating the measurements with threshold values, a rating of 0–100 is assigned to each criterion. Also, a score of the land unit is given a rate of 0–100 by calculation as described by the three methods discussed above. The method of maximum limitation involves the selection of the most restricting rating and/or considering it as the total score for a land unit. Soil series were first classified for their suitability by matching their characteristics with the FAO requirements in Table 2. The suitability class of the soil was indicated by its most limiting characteristics.

TABLE 3 Land suitability classification.

FAO symbol	Suitability	Land index	Description
Class S1	Highly suitable	75–100	Land with no significant limitation to sustain the application of an intended use, or minor limitations that will not significantly reduce productivity and will not raise inputs above an acceptable level
Class S2	Moderately suitable	50–75	Land with limitations that are moderately severe for sustained application of a given use. Limitations will reduce productivity or benefits to increase the required inputs to the extent that the overall advantage to be gained from the use. Although attractive, it will be inferior to that expected from Class S1
Class S3	Marginally suitable	25–50	Land having limitations that are severe for sustained application of a given use and will reduce productivity or increase inputs required (expenditure)
Class N	Not suitable	0–5	Land with qualities that preclude the sustained use of land under consideration

Source: Modified from Sys et al. (1991) and Hagos et al. (2022).
NB: Land with limitations that are moderately severe for sustained application for a given use. Limitations will reduce productivity or benefits to increase the overall advantage to be gained. Although, attractive, it will be lower to that expected from Class S1.

TABLE 4 Productivity index and corresponding suitability classes.

Limitation	Rating
Slight-none	100–95
Slight	94–85
Moderate	84–60
Severe	59–40
Very severe	39–0
(1) can be corrected	39–20
(2) cannot be corrected	19–0

TABLE 5 Soil and land indicators and its affected properties for a high soil resilience.

Soil and land indicators	Biochemical and physical processes affected
Soil depth	Rooting depth; filter, buffer and transformation capacities; pollutant and nutrient storage
Slope	Erosion and loss of soil
Clay + silt	Formation of clay- humus complexes and aggregation; increases surface area of the soil and amount of plant available water; decreases the leaching potential
SOC	Most physical, chemical and biological process: increases water holding capacity, soil structure, aggregation filter transformation and buffer capacity and bulk density; represents a source of plant nutrients, source of energy for soil organisms
pH and CEC	Mobility and availability of nutrients; leaching potential; biodiversity

SOC, soil organic carbon; CEC, cation exchange capacity.
Soil and land indicators adopted from Schiefer et al. (2016).

For the parametric method, each limiting characteristic was rated.

Furthermore, the productivity index for each soil series (pedon) was calculated using Equation 1 above. In all, five (5) land quality factors, thus climate (c), topography (t), soil physical properties (s), wetness (w), and fertility (f), were used for the assessment. Only a member of each group was used to calculate the overall suitability index because there was a strong correlation among variables of the same group (e.g., texture and structure) (Ogunkunle, 1993). All the lowest characteristics for rating each land quality group were substituted into the suitability equation for the actual suitability index calculation formulae. Regarding the potential suitability index, the observed corrective limitation was no longer a constraint. Finally, the suitability indices were assigned to land suitability classes following the Sys ratings (Sys, 1985; Sys et al., 1991, 1993) (Tables 3, 4).

2.4. Determination of soil color

The Munsell Color Chart, a standard system for soil color description was used. The Munsell color notations are systematic, numerical and letter designations of three parameters (hue, value and chroma). A small piece of soil was compared with the standard color chips in the soil color book. Each color chip was described by three components: hue, value and chroma. Thus, hue represents the dominant spectral color which refers to the redness or yellowness in the soil. The value refers to the relative lightness or darkness of a color (amount of reflected light), a value of zero (0) denotes black. Chroma signifies the purity of the dominant color (strength of the color), and a chroma of zero (0) being neutral gray. For example, the notation of 2.5 YR5/6 means a hue of 2.5 YR, value of 5 and a chroma of 6. The equivalent soil color name is “red.”

2.5. Land scoring for sustainable intensification

In order to quantify SI, six (6) land and soil characteristics indicating the resilience and performance of land were used. For each land unit the measured values for the indicators were derived from the field and analyzed according to defined threshold values (Tables 5, 6). By summation of all scores, a minimum value of 6 and a maximum value of 20 (four points for SOC, Clay + Silt content, and three points each for pH, CEC, soil depth, and slope) could be attributed to a land unit. The total points were

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grouped into four different categories of SI potential. The land with the lowest quality has only a final score between 6 and 10 (category 1). This implies that the soil has intrinsic properties which cannot support sustainable intensification. Land in category 2 can show medium or good conditions (score > 10), but one or even more indicators are in a poor condition. Therefore, intensification is possible only at a high risk. A score between 11 and 15 represents medium (category 3). This implies a poor potential for SI. This means that intensification should be done with much caution. For category 4 a total score between 16 and 20, represents soils which can compensate environmental impacts through agricultural production. This implies that soils of this nature can be recommended for intensive agriculture under the precondition that it can be managed sustainably.

2.6. Statistical analysis

All statistical analyses were performed with Excel and SPSS version 20.

3. Results

3.1. Physical and chemical composition of soils

Moist soil surface color differed among soil types. The average moist color reading ranged between 2.5 YR 3/4 (*Bediesi series*) to 10YR 6/3 (*Changnalili series*) for the A horizon (Table 7). For B

TABLE 6 Threshold levels and scoring of land indicators for sustainable intensification (SI).

Land indicators	Excellent (4)	Good (3)	Medium (2)	Poor (1)
SOC (%)	>4	2–4	1–2	<1
Clay + Silt (%)	>50	35–50	15–35	<15
pH (1:2.5 w)	–	6.5–8.0	5.5–6.5	<5.5; >8
CEC (cmol $_{(+)}$ kg^{-1})	–	>25	10–25	<10
Soil depth (cm)	–	>60	30–60	<30
Slope (%)	–	<8	8–15	15–25

Score for each indicator is given in parenthesis.
SOC, soil organic carbon; CEC, cation exchange capacity.
Soil and land indicators adopted from Schiefer et al. (2016).

TABLE 7 Morphological properties (range) and classification of soils in the Nkoranza district.

Properties	Classification					
	Bediesi series	Sutawa series	Kpelesawgu series	Changnalili series	Damongo series	Murugu series
Thickness (cm)						
Surface	7–23	13–27	6–23	9–23	10–23	8–23
Subsurface	>100	>100	<100	<100	>100	>100
Color (moist)						
Surface	2.5YR 3/4	7.5YR 4/4	10YR 4/2	10YR 6/3	10YR 3/3	7.5YR 4/4
Subsurface	2.5YR 4/6	7.5YR 4/6	10 YR 5/6	10YR 4/2	2.5YR 4/6	5YR 5/3
Texture						
Surface	SL	SCL	SL	SL	LS	LS
Subsurface	SL/SCL	SCL/CL	LS/SL/CL	SL/L	SL/SCL	SL/SCL
Structure						
Surface	Granular	Granular	Granular	Crumbly	Granular	Granular crumbly
Subsurface	Sub-angular blocky	Sub-angular blocky	Sub-angular blocky	Sub-angular blocky	Sub-angular blocky	Sub-angular blocky
Parent material	Sandstone	Sandstone	Clay shale	Clay shale	Sandstone	Sandstone
Vegetation	Forest	Forest	Savannah	Savannah	Savannah	Savannah
Land use	Forest	Fallow	Grassland	Fallow	Cropland (maize)	Savannah woodland
WRB/FAO classification	Haplic Luvisol	Plinthic Luvisol	Dystric Plinthosol	Gleyic Plinthosol	Rhodic Luvisol	Haplic Luvisol

SL, Sandy loam; SCL, Sandy clay loam; CL, Clay loam; LS, Loamy sand.
Source: Modified from Soil Survey Staff (2014).

horizon, soil color ranged from 2.5YR 4/6 in *Bediesi* and *Damongo series* to 10 YR 5/6 in *Kpelesawgu series* (Table 7).

The soils are deep (>100 cm), well-drained and gravel-free. The results from textural analysis indicate that these soils ranged from sandy loam to sandy clay loam (Table 8). The percentage of sand varied between 60% *(Changnalili series)* and 81% *(Damongo series)* for 0 to 20 cm. For percentage silt, it ranged between 15.2% *(Damongo series)* and 36% *(Changnalili series)* for the 0 to 20 cm. Also, the percentage of clay varied between 2.5% *(Murugu series)* and 6% *(Sutawa series)*.

Chemically, soil pH ranged from 5.20 to 6.60 (Table 9). The percentage of SOC ranged from 0.55% to 2.02%. The concentration of Ex. K ranged from 0.05 to 1.41 to 86.06 mg kg^{-1}. For Ex. K, *Sutawa series* had the highest (1.41 cmol $_{(+)}$ kg^{-1}), followed by *Bediesi* (0.30 cmol $_{(+)}$ kg^{-1}), *Kpelesawgu* (0.19 cmol $_{(+)}$ kg^{-1}) and *Murugu* (0.15 cmol $_{(+)}$ kg^{-1}). However, Changnalili and *Damongo series* recorded the lowest (0.05}. The concentration of available phosphorus (Av. P) ranged from 2.18 to 12.32 mg kg^{-1}. Within soil series, Av. P followed the order: *Bediesi* (12.32 mg kg^{-1}), *Kpelesawgu* (7.65 mg kg^{-1}), *Sutawa* (6.79 mg kg^{-1}), *Changnalili* (6.50 mg kg^{-1}), Murugu (3.12 mg kg^{-1}), and *Damongo series* (2.18 mg kg^{-1}). Base saturation ranged from 67.0 and 98.89%. For soil types, base saturation followed the order: *Sutawa* > *Damongo* > *Bediesi* > *Murugu* > *Kpelesawgu* > *Changnalili series* (Table 9). Also, CEC ranged from 3.63 to 12.63 cmol $_{(+)}$ kg^{-1}. Micronutrient cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) varied in all soil series. *Bediesi series* had the highest concentration of these cations. Also, we observed that cation exchange capacity varied between 3.61 cmol $_{(+)}$ kg^{-1} in *Changnalili series* and 12.63 cmol $_{(+)}$ kg^{-1} in *Bediesi series*. Within the soil series, mean values recorded were in the order: *Bediesi* > *Sutawa* > *Kpelesawgu* > *Damongo* > *Murugu* > *Changnalili series*. These results stressed a high potential for soil nutrient leaching in all soil series except *Bediesi series*. With an EC of > 4 dS m^{-1} (Table 9), all soils encountered had negligible effects of salinity.

Pearson correlation values >0.70 between physico-chemical properties indicate that most of the indicators positively correlated with each other (Table 10). Organic carbon positively correlated with TN (0.94**). Also, CEC positively correlated with pH (0.74**), Ex. Ca (0.96**), Ex. Mg (0.89**), ECEC (0.99**) and negatively correlated with Ex. Acidity (−0.73**). With respect to percentage BS, it correlated with pH (0.93**), Ex. Ca (0.82**), Ex. Mg (0.79**), CEC (0.85**), ECEC (0.82**) and negatively correlated with Ex. Acidity (−0.90**). Sand recorded a negative correlation between Silt (−0.92**) and Clay (−0.72**). From the above, soil physico-chemical processes tend to function simultaneously. However, the trends are broad and high with a correlation coefficient ranging between 0.01 and 0.99 and −0.02 and −0.92 (Table 10).

TABLE 8 Soil physical properties for the 0–20 cm soil depth.

Soil series	Sand (%)	Silt (%)	Clay (%)	Soil texture
Bediesi	73.1	23.0	3.9	SL
Satawa	72.8	21.1	6.03	SCL
Kpelesawgu	67.5	28.5	4.0	SL
Changnalili	60.5	36.5	3.0	SL
Damongo	81.0	15.2	3.8	LS
Murugu	80.2	17.3	2.5	LS

SL, sandy loam; SCL, sandy clay loam; CL, clay loam; LS, loamy sand.

3.2. Land suitability evaluation for maize cultivation

The rating of land and/or soil characteristics with the requirements of maize (Tables 2, 7) produced suitability classes for maize (Table 11). Most of the soil series encountered were marginally suitable (S3) for parametric and non-parametric methods (Tables 12, 13). The major limitations observed were related to soil texture and structure. These two physical properties of the soil directly affect water-holding capacity, permeability, and other physical properties for the non-parametric (potential) rating (Table 13). Other soil limiting factors were drainage, soil fertility (as measured by CEC, soil organic carbon, organic matter, and total nitrogen content) for the non-parametric (actual) rating.

3.3. Physical and chemical quality index

3.3.1. Physical quality index (PQI)

Soil suitability for maize cultivation was based on several indices for the six major soil series identified in the Nkoranza

TABLE 9 Chemical characteristics (ranges) of soil series for the 0–20 cm soil depth.

Soil series	pH	SOC	TN	Av. P	Ex. Mg	Ex. K	CEC	Mg:K	EC	BS
		(%)	(%)	(mg kg^{-1})	(cmol $_{(+)}$ kg^{-1})			Ratio	(dS m^{-1})	(%)
Bediesi	6.30	2.02	0.28	12.32	2.80	0.30	12.63	9.33	0.17	88
Sutawa	6.40	0.97	0.14	6.79	2.40	1.41	8.99	1.70	0.08	98
Kpelesawgu	5.70	1.24	0.05	7.65	2.10	0.19	7.11	11.05	0.10	82
Changnalili	5.20	0.55	0.04	6.50	0.80	0.05	3.63	16.00	0.08	67
Damongo	6.60	0.61	0.06	2.18	0.20	0.05	5.58	4.00	0.06	90
Murugu	5.70	0.88	0.13	3.12	1.40	0.15	5.30	9.33	0.07	84

SL, sandy loam; SCL, sandy clay loam; CL, clay loam; LS, loamy sand.

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TABLE 10 Pearson correlation matrix for the 0–20 cm soil depth.

Variables	Sand	Silt	Clay	pH	SOC	TN	SOM	Ex. Ca	Ex. Mg	Ex. K	Ex. Na	Ex. Ac	CEC	ECEC	BS	Av. P	EC
Sand	1																
Silt	**0.92****	1															
Clay	**0.72****	0.41	1														
pH	−0.04	0.06	−0.02	1													
SOC	0.69**	−0.58*	−0.61*	−0.04	1												
TN	0.54*	−0.42	−0.54*	0.08	**0.94****	1											
SOM	0.69**	−0.58*	−0.61*	−0.04	**0.99****	**0.94****	1										
Ex. Ca	0.21	−0.24	−0.08	**0.70****	0.24	0.29	0.24	1									
Ex. Mg	−0.35	0.29	0.32	0.67**	−0.26	−0.17	−0.26	**0.74****	1								
Ex. K	0.16	−0.36	0.26	−0.13	0.18	0.31	0.18	0.18	−0.15	1							
Ex. Na	−0.32	0.34	0.16	0.43	−0.54*	−0.53*	−0.54*	0.36	0.63*	−0.41	1						
Ex. Ac	0.18	−0.16	−0.14	**−0.95****	0.17	0.05	0.17	−0.68**	−0.68**	0.10	−0.47	1					
CEC	0.01	−0.05	0.06	**0.74****	0.04	0.11	0.04	**0.96****	**0.89****	0.05	0.52*	**−0.73****	1				
ECEC	0.03	−0.07	0.05	0.69**	0.06	0.12	0.06	**0.96****	**0.88****	0.07	0.51*	−0.68**	**0.99****	1			
BS	−0.05	0.02	0.08	**0.93****	0.03	0.16	0.03	**0.82****	**0.79****	0.02	0.30	**−0.90****	**0.85****	**0.82****	1		
Av. P	0.25	−0.41	0.16	0.13	0.06	0.08	0.06	0.51*	0.32	0.58*	0.21	−0.14	0.48	0.50*	0.25	1	
EC	−0.55*	0.38	0.64*	−0.30	−0.20	−0.13	−0.20	−0.12	0.26	0.26	−0.09	0.22	0.00	0.02	−0.06	0.30	1

Bold values represent Pearson's correlation ($r \geq 0.70$). * and ** indicate correlation is significant at $p < 0.05$ and $p < 0.01$, respectively (two-tailed).
CEC, cation exchange capacity; B.S., base saturation; pH, soil hydrogen concentration; T.N., total nitrogen; Av. P, available phosphorus; SOC, soil organic carbon; Ex. Ca., exchangeable calcium; Ex. K, exchangeable potassium; Ex. Mg, exchangeable magnesium; Ex. Na, exchangeable sodium; E.C., electrical conductivity; ESP, exchangeable sodium percentage.

TABLE 11 Parametric suitability class scores of representative pedons of soil series.

Land qualities	Soil series					
	Bediesi series	Sutawa series	Kpelesawgu series	Changnalili series	Damongo series	Murugu series
Climate (c):						
Annual rainfall (mm)	S1 (100)	S1 (100)	S1 (100)	S1 (100)	S1 (100)	S1 (100)
Length of dry season (months)	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)
Mean annual maximum temp. (°C)	S1 (95)	S1 (95)	S1 (95)	S1 (95)	S1 (95)	S1 (95)
Average daily minimum temp. (°C)	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)
Mean annual temp. (°C)	S1 (95)	S1 (95)	S1 (95)	S1 (95)	S1 (95)	S1 (95)
Relative humidity (%)	S1 (100)	S1 (100)	S1 (100)	S1 (100)	S1 (100)	S1 (100)
Topography (t):						
Slope (%)	S1 (95)	S1 (100)	S1 (100)	S1 (100)	S1 (95)	S2 (85)
Wetness (w):						
Drainage	S1 (100)	S1 (100)	S2 (85)	S2 (85)	S1 (100)	S1 (100)
Soil physical properties (s):						
Texture	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)
Structure	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)
Coarse fragments (Vol %)	S1 (95)	S1 (95)	S1 (95)	S1 (95)	S1 (95)	S1 (95)
Depth (cm)	S1 (100)	S1 (100)	S1 (100)	S1 (100)	S1 (100)	S1 (100)
Fertility (f):						
CEC (cmol $_{(+)}$ kg^{-1})	S1 (95)	N1 (40)	N1 (40)	N1 (40)	N1 (40)	N1 (40)
BS (%)	S1 (100)	S1 (100)	S1 (100)	S1 (95)	S1 (100)	S1 (100)
pH (1:2.5)	S1 (100)	S1 (100)	N1 (40)	S3 (60)	S1 (100)	S2 (85)
TN (%)	S1 (100)	S2 (85)	S3 (60)	N1 (40)	S3 (60)	S2 (85)
Av. P (mg kg^{-1})	S2 (85)	S3 (60)	S3 (60)	S3 (60)	N1 (40)	S3 (60)
SOC (0-20 cm) (%)	S1 (100)	S1 (95)	S1 (95)	S3 (60)	S2 (85)	S1 (95)
Ex. Ca (cmol $_{(+)}$ kg^{-1})	S1 (100)	S2 (85)	S2 (85)	S2 (85)	S2 (85)	S2 (85)
Ex. K (cmol $_{(+)}$ kg^{-1})	S1 (100)	S1 (95)	S1 (95)	S2 (85)	S2 (85)	S1 (95)
Ex. Mg (cmol $_{(+)}$ kg^{-1})	S1 (100)	S1 (100)	S2 (85)	S1 (100)	S2 (95)	S1 (95)
Ex. Na (cmol $_{(+)}$ kg^{-1})	S1 (100)	S3 (60)	N1 (30)	N1 (30)	S3 (60)	S3 (60)
Salinity and alkalinity (*n*):						
EC (dS m^{-1})	S2 (85)	S1 (100)	S1 (95)	S1 (100)	S1 (100)	S1 (100)
ESP (%)	S1 (100)	S1 (100)	S1 (100)	S1 (100)	S2 (85)	S1 (100)
Aggregate suitability:						
Actual/Current	S1 (78)	S3 (34)	S3 (31)	S3 (31)	S3 (33)	S3 (31)
Potential	S1 (82)	S2 (72)	S2 (66)	S2 (66)	S2 (70)	S2 (66)

CEC, cation exchange capacity; B.S., base saturation; pH, soil hydrogen concentration; T.N., total nitrogen; Av. P, available phosphorus; SOC, soil organic carbon; Ex. Ca., exchangeable calcium; Ex. K, exchangeable potassium; Ex. Mg, exchangeable magnesium; Ex. Na, exchangeable sodium; E.C., electrical conductivity; ESP, exchangeable sodium percentage. S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N1, not suitable.
Source: Modified from Sys et al. (1991).

(north and south) district. The climatic index (CI) for *Bediesi, Sutawa, Kpelesawgu, Changnalili, Damongo,* and *Murugu series* had a value of S1 (80) (Table 12). A pedological index consisting of soil texture, structure, coarse fragment, and depth for various soil series computed had a value of S2 (71).

3.3.2. Chemical quality index (CQI)

Results indicated that the soil fertility index (SFI) for maize varied between 30 (S3) and 95 (S1). Thus, soils were moderately suitable due to a slight climatic (80%) and pedological limitation (71%). However, the fertility index (SFI) for *Bediesi, Sutawa,*

TABLE 12 Soil index and land suitability class for maize.

Land qualities	Bediesi series	Sutawa series	Kpelesawgu series	Changnalili series	Damongo series	Murugu series
Climatic index (Ic):	S2 (80)	S2 (80)	S2 (80)	S2 (80)	S2 (80)	S2 (80)
Pedologic index (It)	S2 (71)	S2 (71)	S2 (71)	S2 (71)	S2 (71)	S2 (71)
Fertility index (If)	S1 (95)	S2 (82)	N1 (30)	N1 (39)	S2 (64)	S2 (66)
Salinity and alkalinity (*n*):						
EC (dS m^{-1})	S1 (85)	S1 (100)	S1 (95)	S1 (100)	S1 (100)	S1 (100)
Aggregate suitability (*n*):						
Potential (IPp)	S1 (78)	S3 (34)	S3 (31)	S3 (31)	S3 (33)	S3 (31)
Actual/Current (IPc)	S1 (82)	S2 (72)	S2 (66)	S2 (66)	S2 (70)	S2 (66)

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N1, not suitable.

TABLE 13 Suitability classifications with rankings of soils of Nkoranza (north and south) district for maize cultivation.

Soil series	Parametric		Non-parametric	
	Actual	Potential	Actual	Potential
Bediesi	S1 (78)	S1 (82)	S2sf	S2t
Sutawa	S3 (34)	S2 (72)	S3f	S2t
Kpelesawgu	S3 (31)	S2 (66)	N1f	S2w
Changnalili	S3 (31)	S2 (66)	N1f	S2w
Damongo	S3 (33)	S2 (70)	N1f	S2s
Murugu	S3 (31)	S2 (66)	N1f	S2ts

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N1, not suitable; f, soil fertility limitation; s, soil physical property limitation; t, topography; w, wetness.

Murugu, Damongo, Changnalili and *Kpelesawgu* were 95%, 82%, 66%, 64%, 39%, and 30%, respectively (Table 12). Concerning salinity, determined by electrical conductivity, *Bediesi* and *Sutawa series* had a slight salinity index of 85 and 95%, respectively. However, *Kpelesawgu, Changnalili, Damongo*, and *Murugu series* had no salinity limitation.

3.4. Soil suitability assessment

3.4.1. Potential soil fertility

Potential fertility includes cation exchange capacity, base saturation, pH, and organic matter. These chemical properties were altered during tillage. All soil series had a suitability rating of N1 (40) for CEC except *Bediesi series,* which had a high suitability rating (S1 (95). Bediesi, Sutawa, Damongo, and Murugu series had an S1 (100) suitability rating for soil pH. *Changnalili* and *Kpelesawgu series* recorded S3 (60), S2 (85), and N1 (40), respectively (see Tables 11, 13). For organic matter, all soil series in Table 13 recorded a high suitability rating of S1 (100), S1 (95), S1 (95), and S2 (85) for the *Bediesi, Sutawa, Kpelesawgu, Murugu,* and *Damongo series,* respectively, except *Changnalili series* S3 (60).

Tables 11, 12 indicate that the fertility rating for CEC varied between S1 (95) for *Bediesi series* and N1 (40) for *Sutawa, Kpelesawgu, Changnalili, Damongo,* and *Murugu series*. All soil series encountered had S1 (100). However, the overall potential suitability (non-parametric) evaluation remains moderately suitable, with topography (t), wetness (w), and soil characteristics (s) as limitations that cannot be easily alleviated (Table 5). *Bediesi* and *Sutawa series* had topography (t) as a limitation factor, and *Kpelesawgu* and *Changnalili series* had wetness (w) as a limiting factor. On the contrary, *Damongo* and *Murugu series* had soil characteristics as a constraint. Regarding potential suitability (parametric), *Sutawa, Kpelesawgu, Changnalili, Damongo*, and *Murugu series* were moderately suitable (S2), except that *Bediesi series* was rated as highly suitable (S1). The potential suitability could be moderately suitable for soils with water conservation, moisture harvesting structures with fertilizer, lime, and organic matter management.

3.4.2. Current/actual soil fertility

Current soil fertility includes all soil properties easily influenced by soil management practices. These are Av. P, Ex. K, Ex. Ca, Ex. Mg, Mg:K ratio, and Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}). When subjected to tillage, soil chemical properties were easily altered in the soil medium. All soil series had high exchangeable cation values. The Mg: K ratio is adequate in all soil series. The concentration of SOC, TN, and Av. P was considered to be low in all soils except *Bediesi series*. All soil series had varied exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}). *Bediesi series* had the highest cation concentration in calcium, magnesium, and potassium with S1 (100) soil suitability ratings. *Bediesi series* recorded the highest concentration of these cations with values above 8.68 cmol $_{(+)}$ kg^{-1} for Ex. Ca, 0.30 cmol $_{(+)}$ kg^{-1} for Ex.

TABLE 14 Selected indicators and their thresholds for evaluating soil resilience.

Soil series	Indicators of soil resilience (SR)					
	Soil depth (cm)	Slope (%)	Clay + Silt (%)	pH (1:2.5)	SOC (%)	CEC (cmol $_{(+)}$ kg^{-1})
Bediesi	>100	2–5	26.9	6.3	2.02	12.63
Sutawa	>100	2–4	27.4	6.4	0.97	8.99
Kpelesawgu	>100	1–2	32.5	5.70	1.24	7.11
Changnalili	>100	1–2	39.5	5.20	0.55	3.63
Damongo	>100	2–5	19.0	6.60	0.61	5.58
Murugu	>100	2–6	19.8	5.70	0.88	5.30

Sites with slopes >25% were excluded from calculations.

TABLE 15 Distribution of soil resilience (SR) classes in the Nkoranza (north and south) districts can be recommended for SI.

Soil series	Soil resilience indices (SRI)						SRI score
	Soil depth	Slope	Clay + Silt	pH	SOC	CEC	
Bediesi	4	3	2	2	2	2	15
Sutawa	4	3	2	2	1	1	13
Kpelesawgu	4	3	2	2	2	1	14
Changnalili	4	3	3	1	1	1	13
Damongo	4	3	2	3	1	1	12
Murugu	4	3	2	2	1	1	13

The soil types and with associated score of its depth estimated from WRB 2014 soil description.
SR = soil resilience and a soil with high resilience can be recommended for sustainable intensification (SI).

K and 2.80 cmol $_{(+)}$ kg^{-1} for Ex. Mg and 0.85 cmol $_{(+)}$ kg^{-1} for Ex. Na. Also, CEC varied between 3.61 cmol $_{(+)}$ kg^{-1} *(Changnalili series)* and 22.4 cmol $_{(+)}$ kg^{-1} for *Bediesi series*. These results stress that there has been an increase in nutrient leaching in all soil series sampled except *Bediesi series*. The overall rating for the non-parametric (actual/current) evaluation for maize is moderately suitable, with fertility (f) and soil physical properties (s) (thus texture and structure) as the limitations. Hence, soil fertility (f) can be amended. Also, for parametric (actual/current) suitability evaluation: *Sutawa, Kpelesawgu, Changnalili, Damongo*, and *Murugu series* were marginally suitable (S3). *Bediesi series* recorded a high suitability rating of S1. Adopting good farm management practices (eg. organic manure, mulching, etc.), can improve the CEC of *Sutawa, Kpelesawgu, Changnalili, Damongo*, and *Murugu series*.

3.5. Sustainable intensification of soil resources

Soil resilience was calculated for bench mark soils (*Bediesi, Sutawa, Kpelesawgu, Changnalili, Damongo and Murugu series*) of the study area. The summation of all indicator scores resulted in a score ranging between 12 and 15 representing a moderate SI potential (category 3; Tables 14, 15). This means the soil resources of the study area possess a low (poor) potential for SI thus, intensification could be done with caution. The most limiting soil indicators were SOC and CEC and this could be managed sustainably to increase SI in the study area. From our study, the soils of Nkoranza (north and south) can be recommended for intensive agriculture (SI) under the precondition that it can be managed sustainably.

TABLE 16 Correlation analysis between parametric actual index (pai), parametric potential index (ppi), and soil resilience index (SRI).

Soil resilience indices (SSI)	PAI	PPI	SRI
PAI	1		
PPI	0.940 (0.003)**	1	
SRI	0.768 (0.037)*	0.599 (0.104)^{ns}	1

**Correlation is significant at the 0.01 level.
*Correlation is significant at the 0.05 level.
^{ns} Correlation is not significant.
PAI, Parametric Actual Index; PPI, Parametric Potential Index; SRI, Soil Resilience Index (SRI).

3.6. Relationship between parametric actual index, parametric potential index, and soil resilience index

From Table 16, parametric potential index (PPI), and parametric actual index (PPI) were significant and strongly correlated ($r = 0.94$, $p < 0.003$). This indicates that as soil suitability (parametric potential index) increases, soil quality and/or health improves. Also, soil resilience index (SRI) and the parametric potential index (PAI) had a significantly high correlation ($r = 0.76$, $p < 0.037$, p being < 0.05), and this means that as soil resilience increases, soil suitability in terms of productivity (yield) for maize increases. This shows that the relationship between PPI and PAI, as well as SRI and PAI are a perfect correlation (Table 16). Hence, it can be deduced that PAI affects the extent of PPI and SRI. However, an insignificant moderate correlation was observed between soil resilience and parametric potential index ($r = 0.59$, $p < 0.104$, p being > 0.05).

4. Discussion

4.1. Physical and chemical characteristics of soils

Soil color readings differed among soil management zones due to cropping and land-use systems practiced by smallholder farmers. Soil color was influenced by the mineralogy and chemical composition of the soil. The presence of manganese oxides imparted the black color to the soil. Also, organic matter in the soil imparted dark brown to black color to the soils sampled. From the above, observed soil colors may have contributed to low organic matter content (Table 7). The abundance of oxidized Fe in highly weathered tropical soils (Young, 1980), may have resulted in the low organic matter. The high Fe-MnO_2 concretions may have accounted for the red to reddish-brown colors in *Bediesi series*. Several research findings observed higher chroma values of red and associated these soils with low fertility (Desbiez et al., 2004; Laekemariam et al., 2016; Laekemariam and Kibret, 2020). The presence of iron compounds imparted the red, and/or brown color. The red or brown color is mostly related to the extent of oxidation, hydration and diffusion of iron oxides in the soil medium (Foth, 1990).

Most farmers consider dark soil colors fertile compared to reddish hues in the Savannah ecological zone (Desbiez et al., 2004; FARM-Africa, 2005; Haileslassie et al., 2006). The results of this study indicated that soil color is influenced by SOM content. The dark color in the A-horizon decreased with depth. Soils found on slopes not saturated with water had reddish and brownish subsoil colors. Thus, soils of this nature are well-drained and aerated. Soils sampled at poorly drained locations had gray-colored B-horizons (Foth, 1990). Erosion often removed the topsoil layer from the shoulder/back slope of high slopes. This left behind thin and light-colored soils with low organic matter compared to soils of foot-slopes or toe-slopes. High organic matter content was associated with thick A-horizons (Table 7) as observed by Mulugeta and Sheleme (2011) in southern Ethiopia.

Soil pH ranges from (slightly acidic) to (neutral) for *Kpelesawgu and Damongo series*. According to Food and Agriculture Organization (FAO) of the United Nations (1985) and Diallo et al. (2016), this range mainly corresponds with productive soils in the humid tropics. Achieving optimal production of maize requires a moderate acidic to slightly basic soil with a pH range of 5.5–7.50 [Food and Agriculture Organization (FAO) of the United Nations, 1976, 1985] and well-distributed rainfall (800–1,200 mm) throughout its growing season. However, although the physical conditions and environmental factors are favorable for maize production, SOM can be improved with fertilizers and other organic resources (e.g., poultry manure). Based on expert opinion, the selected soil properties (Tables 1, 2, 5) (Mandal et al., 2017) can be improved. Increasing the suitability of soils can improve maize yield in the short and long term in the study area. Soil pH affects soil biological activity, and the availability of nitrogen to plants can also serve as an essential chemical indicator for soil fertility (Diallo et al., 2016). Soil pH influences plant growth and increases the bioavailability of soil nutrients and the activity of soil microbes (Diallo et al., 2016).

The CEC levels were in the order: *Bediesi* > *Sutawa* > *Kpelesawgu* > *Damongo* > *Murugu* > *Changnalili series*. *Bediesi series* had a higher CEC compared to the other soil types due to high surface organic matter. Thus, CEC of a soil is controlled by organic matter and clay content. A CEC of <12 cmol $_{(+)}$ kg^{-1} is low due to the low availability of organic matter. The variability of CEC within soil series explains the differences in the ability of these soils to hold positively charged ions affecting the stability of soil structure, nutrient availability, soil pH, and the response of these soils to fertilizer when applied (Crewett and Korf, 2008). This finding is in line with McAlister et al. (1998), who stressed that CEC varies with a change in percentage of clay, type of clay, pH, and the amount of SOM among soil types. Base saturation followed the order: *Sutawa* > *Damongo* > *Bediesi* > *Murugu* > *Kpelesawgu* > *Changnalili series*. Soil pH is a major factor in determining the percentage of base saturation of soils. According to Brady et al. (2008), soils of the tropics have a variable charge system, and this charge on the exchange complex gives the soil the strength to attract positively charged basic ions.

Therefore, the higher the soil pH (8.5), the higher the negative charges created and the higher the basic cations absorbed by the soil. The more cations absorbed, the higher percentage of base saturation. *Damongo, Sutawa*, and *Bediesi series* had a relatively higher pH than *Murugu, Changnalili,* and *Kpelesawgu series*. This could be due to leaching of basic cations in the latter, giving rise to a relatively lower soil pH resulting in a lower base saturation in *Changnalili series*. *Damongo, Sutawa,* and *Bediesi series* had enough vegetation cover to check the leaching of basic cations, and this in the long-term increased soil pH and base saturation. The concentration of soil organic matter and exchangeable cations was low, indicating that the soils are inherently low in fertility. This implies that soil pH influences the efficiency of plant growth. Soil organic matter and exchangeable cations represent actual and/or potential soil fertility (PSF) (Diallo et al., 2016). When soil is mismanaged, it loses its fertility after years of cultivation. In a similar research, Lal (1996) observed a rapid decline in SOM after intensive cultivation. The low soil fertility could be attributed to a decrease in soil pH due to absorption of nutrients by plants and leaching of basic cations beyond plant roots.

4.2. Suitability of soils for maize production

Land suitability assessment focus on crop requirements, soil type, and landscape attributes that influence cultivation. For the parametric evaluation process (potential) for maize, the soils of the study site showed moderate suitability for maize production (Tables 11–13). However, except *Bediesi series*, all other pedons were rated severe for the actual parametric evaluation. The limitation can be corrected (see Tables 12, 13). The parametric and non-parametric methods classified land units as S2 (highly suitable) and S3 (marginally suitable). The chemical characteristics of the soils were the dominant limiting factors that affected the suitability of land for maize farming in the Nkoranza district.

Concerning pedogenesis and the addition of organic inputs, organic matter is low (Wang et al., 2014). As a result, these soils hardly store organic matter in the form of organic carbon. Also, inappropriate farming practices depleted soil nutrients in the identified soil series. Therefore, application of poultry manure which is abundant in Nkoranza district can be used to restore soil nutrient stocks, and improve soil quality (Yimer et al., 2007). From the above discussion, the main limitation (see Table 13) is soil nutrient deficiency, not climate or topography, because the water need for maize is not greater than the edaphic conditions of the surrounding environment (Diallo et al., 2016). With the significant limitation identified as chemical degradation, these soils would be highly suitable for maize production, if much attention is paid to soil management. Also, these smallholders can use poultry manure from the vast poultry industry in the Nkoranza district to enrich soil fertility on their farms. The use of integrated soil fertility management practices can restore the chemical limitation of these soils.

4.3. Soil fertility, a major limitation to maize growth and development

Table 11 indicates land suitability evaluation for maize cultivation. Potential soil fertility based on cation exchange capacity, base saturation, organic carbon, and soil pH indicated that these soils have a limitation. The soils in Tables 7, 9 had different levels of fertility limitations due to different parent materials. Sandstone had more fertile soils and was richer in plant nutrients than those found in old sediments due to abundant weatherable primary minerals in these soils. These physical properties influence soil fertility by controlling the release and supply of nutrients. Soil physico-chemical parameters, as influenced by parent material, directly influence soil fertility for maize production in the transition zone of Ghana. Maize growth and development depend on the potential of the soil parent material to supply nutrients. Climate is not a significant limitation to maize production because mean annual maximum temperature promotes favorable soil moisture conditions for plant growth and development. As a result, good soil management techniques are required to increase soils suitability ratings for maize production. Water is important during the growth and development stages of maize because a deficit or excess can result in a low yield. Several studies indicated that poor drainage reduces maize yield by affecting net photosynthesis, stomata conductance, and transpiration. Areas with high clay content can be managed by establishing drainage systems that remove excess water to promote maize root development.

Soil physical characteristics had no significant limitations except for sites with very high clay content. Maize grows well in soils with sandy clay loam texture with an optimal water table depth (50–60 cm). The low values of Ex. K in these soils are due to low CEC and high amounts of rainfall that promote the leaching of basic cations. Also, the farmers are smallholders who engage in crop production in a fragile environment with little or no resources for good agronomic practices. In recent years, soil degradation through inappropriate farming practices such as uncontrolled grazing and bush burning with low fertilizer use has increased. Appropriate soil fertility management for K fertilization is required to improve yield. Potassium is the most important nutritional factor that determines maize yield because K plays a major role in the proper functioning of the stomata and prevents droughty conditions. Also, its availability promotes the transportation of assimilates from photosynthesis, assists in enzyme activation, and makes the maize plant disease resistant. Soil fertility evaluation results indicated a low Mg:K ratio due to the relatively low Ex. Mg and a high Ex. K values. This means excess K ions depress the uptake of other cations such as Mg^{2+} ions. Low P availability was a major constraint to maize production in the study area. The application of phosphorus and magnesium amendments could increase maize yield. Understanding the nature and variability of soil properties with respect to soil fertility and maize are critical issues to consider in soils formed on sandstone and clay shale parent materials in the transition zone of Ghana.

4.4. Limiting factors to sustainable intensification in the study area

This study reveals how soil can be included in discussions on where to find land to produce more food to feed the growing population with the adoption of soil resilience principles (Schiefer et al., 2016). The maize fields sampled had soils with moderate soil resilience (Table 15). The soils intrinsic characteristics are favorable for intensification if and only the main limiting factor thus SOC and CEC are managed carefully to avoid causing low soil resilience. The relationship between CEC and other indicators (pH, Ex. Ca, Ex. Mg, and Ex Acidity) as well as between SOC and Sand, Silt and Clay confirms the fact that these physico-chemical properties function simultaneously (Table 10) and at a moderate capacity (Tables 14, 15). Thus, CEC is the soils capacity to retain organic and inorganic positively charged compounds in the soil medium.

Inappropriate land use management has resulted in the degradation of soils hence rejuvenating the negative effects of poor parent material, terrain characteristics and in a changing climate has affected soil resilience (Lal, 1997). The processes of soil resilience involve the mechanisms that influence the soils' ability and rate to recover after disturbance. Good soil management results in the provision of other ecosystem services such as biodiversity, water storage, carbon storage, flood and/or drought regulation etc. According to van Ittersum et al. (2013), the evaluation of the potential of land for SI is important because this could serve as a guide to evaluate yield gap potential including the differences associated with climatic conditions and cropping systems on farmer's fields locally and regionally. This can assist in the prediction of the future potential of sustainable intensification of smallholder agriculture in Ghana.

4.5. Recommended land use management options for sustainable intensification of small farms in the study area

From the above discussion, the integration of organic and inorganic resources into soil fertility management options (compost, manure, plant residue, etc.) and organic residues can be use by farmers (Bationo et al., 2007; Bekunda et al., 2010) during the beginning of the major and minor farming seasons to increase maize yield from the current 1.75 t/ha in the Nkoranza (North and South District). Also, site specific fertilizer application (Tetteh et al., 2017, 2018) compared to the blanket fertilizer application [mostly two (2) bags of 50 kg NPK and 1 bag of 50 kg of Urea or Sulfate of Ammonia per ha] is recommended for small farm holders in the Nkoranza (north and south) districts. Thus, the relevance of mineral fertilizer use in the intensification of food production on small farms cannot be under estimated especially in areas with soils deficient in nutrients.

According to Tetteh et al. (2018), combined application of organic fertilizer (poultry manure at 2.5 T ha^{-1}) with 60 kg N ha^{-1} of mineral fertilizer yielded the same yield as the application of sole 90 kg N ha^{-1}. Hence, the application of 90 kg N ha^{-1} yielded optimum economic returns in the Forest-Savannah Transition Zone (FSTZ). Thus, the current fertilizer recommendation for maize with respect to NPK recommendation is N-P_2O_5-K_2O:90-60-60+1.7 Zn and for recommended blends per hectare is N-P_2O_5-K_2O:15-20-20+0.7 Zn (8 bags/ha + 2bags/ha urea) for the FSTZ of Ghana. Also, the recommended fertilizer formulae blend is N-P_2O_5-K_2O:15-20-20 +0.7 Zn (6 bags/ha + 2 bags/ha urea) (Tetteh et al., 2017, 2018). The mean yield from field validations of the new fertilizer recommendations using the new blends or formulae yielded a mean of 6.0 t/ha. Thus, on a fertile soil with recommended fertilizer application and planting at the onset of the major and minor rainy season, a grain yield ranging between 5 to 8t/ha with high returns is expected compared to the current yield of 1.75 t/ha for Nkoranza (North and South) district and 1.6t/ha of national average yield for Ghana. This would assist improve the efficiency and profitability of fertilizer use on smallholder maize farms in the Nkoranza (north and south) districts in the Forest Transition Agro-ecological Zone of Ghana.

The creation of an enabling environment through the formulation of policies and institutions to facilitate the intensification process in smallholder agricultural production systems should be a national priority. Also, investments into agricultural research as documented in the Maputo declaration that at least 10% of national budgetary allocations should be invested in agriculture and rural development (African Union, 2003) could strengthen innovative systems that increase productivity on small farms. These investments should include the provision of credit (loans, subsidies etc.), input (fertilizers, herbicides, and pesticides) and the creation of markets for agricultural produce. These according to Schut et al. (2016) could address 70% of the constraints associated with the sustainable intensification process at the local, regional and national level in Ghana.

5. Conclusion

The evaluation methods used for soil suitability assessment indicated that climate, soil texture, and topography were suitable for maize cultivation. All pedons were moderately suitable (S2) for the parametric and marginally suitable (S3) for the non-parametric method. The limitations relating to texture and structure directly affected soil water holding capacity and soil permeability. The primary soil fertility constraints were CEC, organic matter, and available P, varied across soil types. The maize fields sampled had soils with moderate soil resilience. The relationship between CEC and other indicators (pH, Ex. Ca, Ex. Mg, and Ex Acidity) as well as between SOC and Sand, Silt and Clay confirms that these physico-chemical properties function simultaneously and at a moderate capacity. Also, pearson correlation revealed a strong significant relationship between parametric actual index (PAI) and parametric potential index and between soil resilience (SRI). This suggests that soil physico-chemical properties can be used to quantify the productivity of soils. Therefore, emphasis on soil management techniques to enhance soil nutrient and moisture-holding capacity can be improved to increase productivity levels of maize. Farm management techniques (e.g., soil and water conservation, moisture harvesting, organic and inorganic fertilizers) are recommended to improve soil nutrient levels. Soil suitability indexing can enable soil quality monitoring in relation to sustainable intensification of agricultural land use so that threats to soil resources and opportunities for sustainable intensification could be identified in the Nkoranza district in the Forest-Savanna Transition Zone of Ghana.

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

JA designed the research, analyzed all data, and wrote the manuscript. JA and BD did field survey and carried out the laboratory experiments. GQ checked for accuracy of data 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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EDITED BY
Francis Tetteh,
Council for Scientific and Industrial Research (CSIR), Ghana

REVIEWED BY
Wasiu Awoyale,
Kwara State University, Nigeria
Emmanuel Amponsah Adjei,
CSIR-Savanna Agricultural Research Institute, Ghana

*CORRESPONDENCE
Jude Ejikeme Obidiegwu
✉ ejikeobi@yahoo.com

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Farmers' perspective toward a demand led yam breeding in Nigeria

Confidence Kalu[1], Ikenna Nnabue[1], Alex Edemodu[2], Paterne A. Agre[2], Patrick Adebola[2], Asrat Asfaw[2] and Jude Ejikeme Obidiegwu[1]*

[1]Yam Research Programme, National Root Crops Research Institute, Umudike, Abia State, Nigeria, [2]International Institute of Tropical Agriculture (IITA), Ibadan, Oyo State, Nigeria

This study seeks to increase the efficiency of yam breeding practice using farmers' insight at the trait and socioeconomic levels. A three-staged multisampling procedure was employed and 792 yam farmers from four geopolitical zones, comprising 10 states and the Federal Capital Territory, Abuja in Nigeria were randomly selected. Farmer's preference criteria and factors pertinent to improving the efficiency of yam breeding in Nigeria were documented. The data obtained were analyzed using a 5-point Likert scale to identify major traits farmers consider in the yam cultivar selection decision. Kendall's coefficient of concordance was used to measure the degree of agreement of ranking among the farmers. Factors influencing farmers' trait preference for yam cultivars were evaluated using a multinomial-ordered logistic regression model. The result revealed that yam varieties with high germination rates, disease-free quality, big tuber sizes, early maturity, and good pounding attributes are held in high esteem. The most critical constraint limiting the production of yam in the study area includes pest and disease attack, climate change, high cost of seed yam, high cost of staking, and weed infestation. Sex, age, access to credit, membership to yam association, total land owned, and years of experience as a yam farmer significantly influence farmers' ability to select yam cultivars with preferred attributes. A strategic effort needs to be given to these farmers' desired yam attributes and factored into developing improved yam varieties for increased adoption and enhanced food security in Nigeria.

KEYWORDS

yam, farmers, traits, constraints, breeding

1. Introduction

Yam (*Dioscorea* spp.) is the common name for a monocotyledonous tuber-producing vine plant with several species (approximately 600) (Mondo et al., 2020). It is widely cultivated as a staple food in Africa, Asia, South America, the West Indies, and the Pacific Islands (Obidiegwu and Akpabio, 2017). Among the cultivated species, the white yam (*Dioscorea rotundata*) is popularly grown in West Africa, while the water yam (*Dioscorea alata*) has a global production outlook (Darkwa et al., 2020). Yam serves as a major source of food and income for many people along the yam value chain (Scott et al., 2000; Maikasuma and Ala, 2013; Agre et al., 2023). Yam has cultural, social, economic, and religious value in most African societies (Obidiegwu and Akpabio, 2017), as well as in most therapeutic potentials (Obidiegwu et al., 2020). Millions of people depend on yam as a major source of calories and nutrition (Degras, 1993; Asiedu and Sartie, 2010). Nigeria ranks as the leading producer of white yams in the world, accounting for 66% (approximately 50.1 million tons) of annual global production (FAO, 2021).

Farming in Nigeria is characterized by smallholder farmers, who typically practice subsistence farming. The major producers of yam carry it out on parcellated plots using crude implements (Nahanga and Vera, 2014; Oseni et al., 2014). While population growth is significantly high, the amount of yam produced per hectare has remained stagnant or is declining (Nahanga and Vera, 2015). The rate of annual increase in yam production has been slowing compared to earlier dramatic increases associated with area expansion (Barlagne et al., 2017). The productivity of yam continues to fall as most farmers are getting about 10 tons/ha when compared to a potential yield of 50 tons/ha in some cultivars (Frossard et al., 2017; Neina, 2021). It is obvious that yam production under the current extensive agricultural practices of expanding into new lands that Nigeria has enjoyed sometimes is not sustainable. It has been predicted that this decrease could be catastrophic unless steps are taken soon to change the situation (Manyong and Nokoe, 2001). This past pattern needs to be reversed to satisfy a growing demand by yam value chain actors. The decline in productivity is partly associated with shortened fallow periods and deteriorating soil fertility, degeneration of popular varieties, increasing levels of field and storage pests and diseases (e.g., nematodes, mealybugs, scales, anthracnose, and viruses), high tuber losses in storage, high costs of labor, scarcity, and high costs of clean (pest-free) planting material. Demand for yam is also prone to demand–supply chain issues related to the limited number of its processed products and poor market linkages.

Considering the aforementioned constraints, the National Root Crops Research Institute Umudike and the International Institute of Tropical Agriculture Ibadan (both in Nigeria) have codeveloped 35 yam varieties for the Nigerian market. The Yam Improvement for Income and Food Security in West Africa (YIIFSWA) project was a major platform for addressing the seed system challenge. A major fallout of this effort was the development of a sustainable formal seed system in Nigeria while developing technologies for high-quality seed yam production. This effort established hubs of commercial and village seed entrepreneurs through the improvement of local capacity for the production of clean seed. A commercial seed yam system that sustainably ensures that smallholder farmers have access to high-quality seed was a major delivery. The scaling of these efforts is ongoing, and we envisage continuous growth. However, there has been a slow uptake of newly developed varieties. It has been acknowledged that the adoption of new food crop varieties in sub-Saharan Africa (SSA) has been relatively slow compared with other parts of the world (Thiele et al., 2021). This limited uptake of new varieties and low varietal turnover could be attributed to the insufficient priority that is given to economic and valuable traits by breeding programs (Goddard et al., 2015). The process of varietal development in crops and their subsequent dissemination and adoption is an intricate activity that begins with setting breeding objectives and emerging a selection strategy for priority traits. It will entail the identification of traits of preference by farmers and end users while incorporating them in product profiles. Otegbayo et al. (2021) set the foundation by identifying textural qualities and color as critical user-preferred quality traits for pounded yam acceptability by the stakeholders including processors, and consumers. We seek to complement the aforementioned study by addressing some other market perspectives that will further enhance the efficiency of the yam breeding system in Nigeria.

Resolving this consultative process requires open discussion and partnership between plant breeders, other researchers, including social scientists, farmers, and other users such as traders and consumers with a view to understand the needs and preferences of different users and their importance (Christinck et al., 2005; Agre et al., 2023). Moreover, in most farming households, there are differences in roles and assets that can lead to the development of specific traits. These preferences may have explicit gender-measurable attributes. Mapping trait information according to the role and position that an actor occupies in the value chain, including gender-specific information produces extensive and relevant information about the variety, their traits, and specific uses. Hence, information on end-user traits is not adequately considered in most varietal adoption studies. We seek to give thoughtful attention to the trait preferences of farmers as the first step in developing a demand-driven breeding program.

2. Materials and methods

2.1. Description of study area

Ten states (Anambra, Ebonyi, Cross River, Edo, Benue, Oyo, Osun, Ekiti, Nasarawa, and Niger) and Federal Capital Territory (FCT) Abuja representing four geopolitical zones (North Central [NC], South West [SW], South East [SE], and South South [SS]) of Nigeria where yams are extensively cultivated were selected for this survey. Two states each were selected from SE and SS while six states were selected from SW and NC. In addition, the FCT which falls within NC was equally considered. The 10 states and FCT surveyed are located in three vegetative belts, namely, the Humid Rainforest, Derived Savanah, and Southern Guinea Savannah agroecological zones. The geographical representation of the coordinates of the study locations is presented in Figure 1.

2.2. Sampling technique and data collection

A total of 792 respondents were chosen from 11 states, namely, Anambra, Ebonyi, Cross River, Edo, Benue, Oyo, Osun, Ekiti, Nasarawa, Niger, and FCT. The respondents for the study were selected through the use of a three-staged multisampling procedure. Two out of three senatorial zones were selected from each state. The selection of two local government areas from each senatorial zone was done purposively. Two rural farming communities were chosen from each of the selected local government authorities (LGAs) through purposive sampling. Nine yam farmers were randomly chosen from among the communities under study, thus resulting in a total of 792 ($11 \times 2 \times 2 \times 2 \times 9$) respondents. The study population was drawn from the group of farmers working under the African Yam Project focusing on major yam-producing states in Nigeria. The sample size was determined, following Yamane (1967), which is expressed in equation 1 as follows:

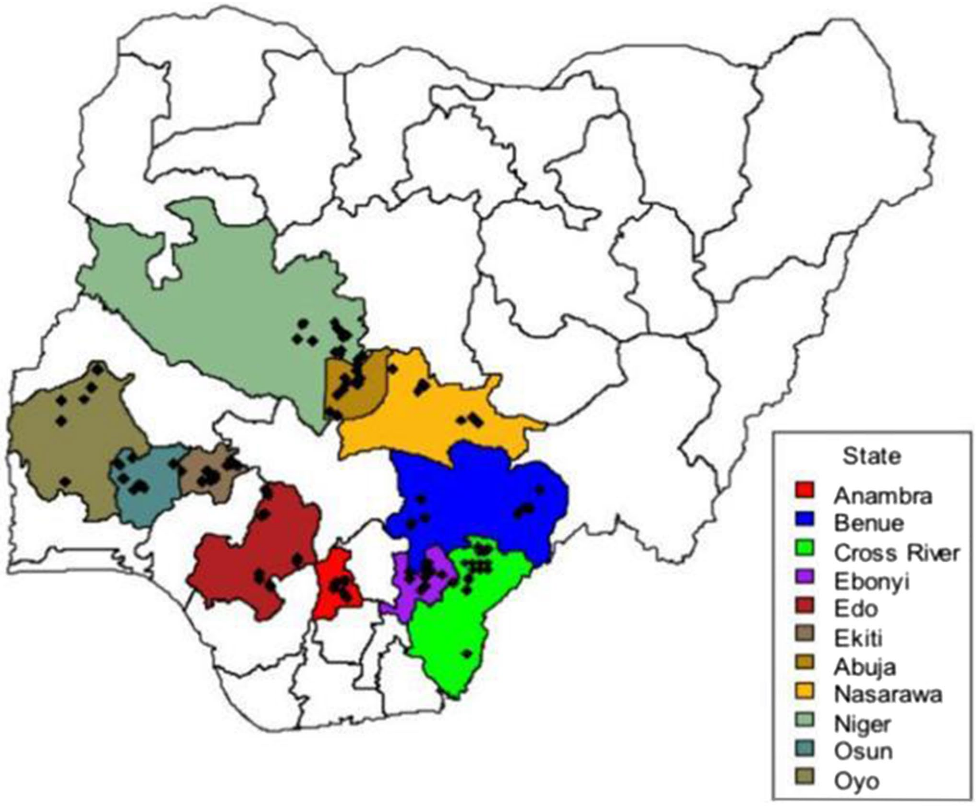

FIGURE 1
Map showing geographical areas of study location in Nigeria. ■ Study sites.

$$N = N / (1 + N(e)^2) \quad (1)$$

where n is the sample size, N is the population size, and e is the level of precision.

The data collected include demographic information, socioeconomic variables, institutional-and farm-level characteristics, consumer trait preference criteria, and production constraints experienced by the farmers in the study areas. Due to incomplete questionnaires and/or inconsistent data, a total of 745 fully completed questionnaires were used for analysis in this study.

2.3. Statistical analysis

A 5-point Likert model and Kendell's coefficient of concordance were used to identify preferred attributes and the degree of agreement in ranking among the farmers across the geopolitical zones. While production constraints were analyzed with the aid of descriptive statistics such as mean, frequency, and percentage, multinomial ordinal logistic regression was used to estimate the influence of sociodemographic parameters such as age, years of experience, farm size, marital status, family size, and education level on farmers' varietal selection decision. The study ascertained the major traits considered by farmers in yam variety selection decision. These traits were categorized into five levels for the purpose of ranking in the following order: "Very Important" (1), "Important" (2), "Moderately Important" (3), "Neutral" (4), and "Not Important" (5). The highest-ranked category was assigned a value of 1. All statistical analyses were done in an open-source R environment version 4.2.2 (R Core Team, 2022) while utilizing the packages, namely, "Tidyverse," "Readxl," "agricolae," "dplyr," "ordinal," "rgdal," "sp.," "rgeos," "raster," and "DescTools."

2.4. Theoretical framework

In an ordered response model, the analysis is usually performed based on less restrictive assumptions. The scores are assumed to be measured on an interval scale; in a real sense, the score represents an order of the responses (Maddala, 1983). The assumption is that the scores represent ordered segments of a utility distribution. In modeling the factors that influence farmers' decision to consider certain traits before selecting a yam variety, the study adopted a qualitative response regression model approach because the dependent variable (preferred traits of importance in yam variety selection decision) was measured qualitatively.

Furthermore, for dependent variables that are not ordered and are polytomous, the use of multinomial logit is most appropriate (Deressa et al., 2010; Etwire et al., 2013). However, it is unsuitable in cases when the dependent variable is ordered, because of its inability to account for the ordinal nature of the dependent variable (Greene, 2003). Under this situation, the use of ordered logit is more proper. Ordered logistic regressions have been employed in empirical studies such as the study by De Groote et al. (2010). This study used ordered logit because yam producers ranked the traits they considered in selecting yam variety and the order of rank was used as the dependent variable.

Participating farmers score a trait of a certain variety in a particular ordered category, driven by a latent, unobserved variable U as expressed in equation 2, which represents utility or indicates a preferred trait in a particular variety. As a substitute for this latent variable U, we observe the scores y, a variable that falls in one of m ordered categories, which in this study lie between "Very Important" (1) to "Not Important" (5). The scores are then connected to the latent variables through the limit points from N_1 to N_{m-1}, which are expressed as follows:

$$y = 1 \text{ if } U < N_1$$

$$y = 2 \text{ if } N_1 \leq U < N_2 \quad (2)$$

$$y = m \text{ if } N_{m-1} \leq U$$

where y's are the ordinal numbers and U represents traits considered in a yam variety selection decision. This can be analyzed using standard quantitative methods, for example, the linear model (Train, 2003). This is explicitly expressed in equation 3 as follows:

$$U_i = \beta^i a_i + \varepsilon_i \quad (3)$$

where U_i is the utility of individual i, a_i is a set of variables influencing the i's utility and choice, β is a vector of parameters to be estimated, and ε_i is the error term.

The probability of the scores y can now be derived from this model. The first outcome's probability, with a set of independent variables, a_i, is expressed in equation 4 as follows:

$$P(y = 1) = P(U < n_i) = P\left(\varepsilon < N_i - \beta^i a\right) \quad (4)$$

The distribution function for error term, ε, needs to be assumed to enable one to estimate these probabilities from the survey data. Here, the logistic distribution is often applied due to its convenient closed for cumulative distribution function (cdf) that is expressed in equation 5 as follows:

$$P(\mathrm{a} < \mathrm{a}) = \frac{1}{\left(1 + e^{-a}\right)} = \frac{e^a}{\left(1 + e^a\right)} \quad (5)$$

The probability for the lowest score can now be derived from the cdf as follows:

$$P(y = 1) = P\left(\varepsilon < n1 - \beta^i a\right) = \frac{e^{n1} - \beta^1 a}{1 + e^{n1} - \beta^1 a} \quad (6)$$

The logs of the probabilities for the different outcomes can be multiplied to obtain the log likelihood of the variables of these outcomes. The coefficients, β, and the cutoff points, n^i, are the outputs of maximum likelihood estimation. This model is known as the ordered logit model (Train, 2003).

The effect of the independent variables of farmers' preferences is quantified by the value of the coefficients but the odds ratios of the cumulative probabilities allow easier interpretation of the result. In deriving the odds ratios, here the cumulative probability of a score m is defined as the probability of a score to be equal to or less than m, and this can be derived from the logistic cdf as follows:

$$P(y \leq m) = \frac{e^{n1} - \beta^1 a}{e^{n1} - \beta^1 a} \quad (7)$$

The odds ratio of an event (q) to occur is the probability it occurs over the probability it does not. This is mathematically expressed as $p(q)/[1 - P(q)]$. For the ordered response model, the odds ratio for the lowest score to occur is $p(y = 1)/1 - P(y = 1)$; conclusively, the cumulative odds ratio is the ratio that a score y falls at or below a certain level, j, or $P(y \leq m)/1 - P(y \leq m)$. The cumulative odds ratio can be derived in equation 8 as follows:

$$\frac{P(y \leq m)}{1 - P(y \leq m)} = \frac{e_m^n - \beta^1 a}{1 + e^{n1} - \beta^1 a} / \left(1 - \frac{e_m^n - \beta^1 a}{1 + e^{n1} - \beta^1 a}\right) = \frac{e_m^n - \beta^1 a}{1 + e^{n1} - \beta^1 a} / \left(\frac{1}{1 + e^{n1} - \beta^1 a}\right) = e^{n1} - \beta^1 a \quad (8)$$

It follows that the logarithm of the cumulative odds ratio is a linear function of the independent variable:

$$\ln \frac{P(y \leq j)}{1 - P(y \leq j)} = \ln\left(e^{n1} - \beta^1 a\right) = n_m - \beta^1 \quad (9)$$

Now, we are interested in the effects of the variable a. For a change of a from a_1 to a_2, we will have a log odds ratio of

$$\left(\frac{P(y \leq m | a = a_2) / 1 - P(y \leq m) | a = a_2)}{P(y \leq m | a = a_1) / 1 - P(y \leq m) | a = a_1)}\right) = \beta^1 (a_2 - a_1) \quad (10)$$

This odds ratio is independent of m. The model is, therefore, referred to as a "proportional odds" model (Mccullagh, 1980). The odds ratios in favor of a high score ($y > m$) vs. a low score ($y''\ m$) are in the same proportion for two different values of a, irrespective of the value of m. The coefficient β can be interpreted as the change in the log odds ratio for a unit change in the explanatory variable, a; so, the log odds ratio of a trait having a low score rather than high to the odds ratio of the trait having a high score rather than low. This ratio is called the log odds ratio and its exponent, $e^{\beta 1}$, represents the odds ratio that an attribute is more considered over the same odds ratio for another attribute.

2.5. Analytical framework

According to Tetteh et al. (2011), the total rank score for each trait was calculated and the trait with the lowest score was interpreted as the most preferred. The coefficient of concordance is analytically expressed in equation 11:

$$W = \frac{12\left[\sum X^2 - (\sum X)^2 / n\right]}{nm^2\left(n^2 - 1\right)} \quad (11)$$

where X is the sum of ranks for traits being ranked, m is the number of farmers, and n is the number of traits being ranked. The coefficient of concordance W was tested for significance using the *value of p*.

3. Results

3.1. Socioeconomic, institutional, and farm-level characteristics of the respondents

Table 1 presents the result of the socioeconomic, institutional, and farm-level characteristics of the respondents by agroecologies. The result shows that 76.9% (SE), 84.4% (SS), 91.3% (SW), and 84.7% (NC) of the respondents from the four regions under study were men. This implies that the cultivation of yam in these geopolitical regions was dominated by men. Yam farming and ownership is regularly associated with gender and class, which represents male accomplishment and social status (Martin et al., 2013). The cultivation techniques of yam have been diversely pronounced as exacting and labor-demanding (Obidiegwu and Akpabio, 2017) because activities such as clearing the forest and making big mounds for planting seed yam require energy. Ohadike (1981) and Chiwona-Karltun (2001) reported that the masculine labor required in yam production contributed to the expansion of cassava production (perceived to be more female-oriented) in the lower Niger State at the turn of the 20th century. This trend was obvious due to the scarcity of men occasioned by war at that time. The result further shows that yam farmers who participated in the study were between the ages of 20 and 83 years. The average age of farmers from SE and SS regions was 49.7 and 48.6 years, respectively, while that of SW and NC were 47.6 and 44.1 years, respectively. This observed age indicates that yam farmers from the study locations were among the young population who have youthful potential for yam productivity in Nigeria. The mean farming experience of the respondents was 24.3 and 24.7 in SE and SS, respectively, while 23.7 and 25.1 were recorded in SS and NC, respectively. More than 70% of the farmers from the four zones under study had access to primary and secondary education. Farmers in the SE region have more years of formal education (43.9%) when compared with those in the NC region (30.3%). Institutional variable results show that most farmers are not members of the yam farmers' association. The percentage of farmers who belong to one association or the other varies across the different regions with SS having the highest value (74.9%). Farmers' ability to access credit in SS was highest with more than 60% of the farmers from SS having access to credit. Most yam farmers were not visited by extension agents during the period of study. Only 11.9 and 17.6% of farmers from NC and SS, respectively, were visited by extension agents. The farm-level information shows that yams were cultivated in a farm size ranging between 0.01 and 30 ha with a mean of 2.68 ha. Yam production was the major source of income for the farmers surveyed as 53% earn more than half of their livelihood from the sale of yam.

3.2. Farmers' preferred traits across gender and cultural patterns in the study area

Table 2 presents the result of the ranked order of traits considered by farmers from SS and SE geopolitical zones of Nigeria in yam variety selection decision. It was observed from the result that yam with a "high germination" rate was the most considered trait in yam variety selection decision across the two geopolitical zones and among male and female yam producers. However, the ranking order of these traits varied from one geopolitical zone to another. High germination, tuber size, and tuber free from rot were among the first three traits that are highly considered by male farmers in SE Nigeria. Female yam farmers in the same region prefer yam varieties that are disease-free with big tuber sizes and high germination rates. Culinary quality such as pounded yam quality was an important trait that male farmers in SS Nigeria consider in yam selection decisions while yam varieties that are free from disease merited the attention of female yam farmers from SS Nigeria. Kendell's coefficient of concordance shows that 30 and 70%, respectively, of male and female farmers from SE, with 55 and 63% of male and female farmers from SS of the sampled population agree with each other on the order of ranking these traits.

Table 3 presents the result of the ranked order of traits considered by farmers from SW and NC geopolitical zones of Nigeria in yam variety selection decision. The result depicts that SW male yam farmers value yam variety that matures early and has high germination with big tuber sizes while female yam farmers consider yam variety that has a high germination rate with good tuber shape with high market value. The result from Table 3 shows that both male and female yam farmers from the NC zone consider tuber size as a major selection criterion. In addition, yam varieties with good pounding attributes were equally considered important as they ranked second and third for male and female yam farmers, respectively. Late maturing variety was the least trait to be considered in yam variety selection decision as it ranked last in all the zones. This trend was observed in both genders. The level of agreement among male and female yam farmers from the two regions was above 50% and highly significant.

3.3. Yam production constraints and accessibility of preferred yam varieties across the study zones

The challenges associated with the declining yam production by surveyed farmers in Nigeria are presented in Table 4. The result as shown in Table 4 confirms that among the 13 identified constraints hindering production, the problem of pest and disease attack (56.3%), climate variability/change (27.5%), high cost of seed yam (13.8%), and high labor cost were the most mentioned by SE yam farmers. In SS, most yam farmers face the problem of pest and disease attacks (50%), high cost of farm inputs (18.8%), and low soil fertility (17.5%). The major challenge for yam farmers in the SW region was a change in climate (61.3%), low soil fertility (33.8%), and low yield (17.5%). The NC yam farmer was constrained by the high cost of farm inputs (72.5%), pest/disease attacks (47.5%), and poor soil fertility (45%). The high cost of farm inputs and declining soil fertility also serve as a hindrance to yam cultivation in NC with recorded values of 72.5 and 45%, respectively. The issue of climate change (61.5%) was experienced more by farmers in the SW zone followed by pest and disease attacks

TABLE 1 Distribution of respondents' socioeconomic, institutional, and farm-level characteristics according to geopolitical zones of Nigeria.

Variables	SE		SS		SW		NC	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Gender								
Male	123	76.86	135	84.38	157	91.28	232	84.67
Female	37	23.13	25	15.63	15	8.72	42	15.33
Total	160		160		172		274	
Age (years)								
21–30	8	5	6	3.75	5	2.905	36	14.184
31–40	42	26.25	38	23.75	52	30.21	77	30.338
41–50	38	23.75	54	33.75	52	30.21	73	28.762
51–60	35	21.875	35	21.875	39	22.659	39	15.366
61–70	30	18.75	23	14.375	24	13.944	27	10.638
71–80	7	4.375	4	2.5			2	0.788
Total	160		160		172		254	
Level of education								
0–6	69	43.125	50	31.25	68	39.78	77	30.338
7–12	63	39.375	67	41.875	65	38.025	68	26.792
13-16	28	17.5	43	26.875	38	22.23	109	42.946
Total	160		160		171		254	
Farming experience								
1–9	29	18.125	19	11.94	42	24.71	60	23.62
10–19	47	29.375	55	34.59	68	40	75	29.53
20–29	38	23.75	50	31.45	32	18.82	67	26.38
30–39	26	16.25	25	15.725	17	10	28	11.02
40–49	15	9.375	8	5.032	9	5.29	17	6.69
50–59	3	1.875	1	0.629	1	0.588	5	1.97
60–69	2	1.25	2	1.258	1	0.588	2	0.79
Total	160		159		170		254	
Household head								
Yes	136	85	134	84.286	160	93.57	221	87.00
No	24	15	25	15.725	11	6.43	33	12.99
Total	160		159		171		254	
Visit of extension agents								
Yes	40	25	28	17.61	72	41.86	30	11.86
No	120	75	131	82.39	100	58.14	223	88.14
Total	160		159		172		253	
Access to credit								
Yes	41	25.63	52	32.71	116	67.44	34	13.39
No	119	74.38	107	67.30	56	32.56	220	86.61
Total	160		159		172		254	
Member to yam cooperative								
Yes	28	18.42	19	11.95	128	74.85	92	36.22
No	124	81.58	140	88.06	43	25.14	162	63.77
Total	152		159		171		254	

(Continued)

TABLE 1 (Continued)

Variables	SE		SS		SW		NC	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
Total land area owed								
0.1–5.0	120	75.00	81	50.625	48	27.91	139	50.73
5.1–10	30	18.75	42	26.25	34	19.77	72	26.28
10.1–20	6	3.75	28	17.5	39	22.67	32	11.68
20.1–30	3	1.875	6	3.75	22	12.79	12	4.38
30.1–40	0	0	1	0.625	5	2.91	6	2.19
40.1–50	1	0.625	2	1.25	7	4.07	9	3.28
50.1–60	0	0	0		17	9.88	4	1.46
Total	160		160		172		274	
Land area planted with yam								
0.01–1	81	50.625	65	40.885	37	21.76	116	45.84
1.01–2	33	20.625	37	23.27	52	30.58	51	20.16
2.01–3	22	13.75	18	11.32	33	19.40	33	13.04
3.01–4	9	5.625	12	7.55	11	6.47	12	4.74
4.01–5	6	3.75	13	8.18	12	7.06	10	3.95
>5.01	9	5.625	14	8.81	25	14.7	31	12.25
Total	160		159		170		253	

Computed from field survey 2021. SE, South East; SS, South South; SW, South West; and NC, North Central.

(33.8%). Farmers' major constraints in NC were the high cost of farm input (72.5%) and the prevalence of pests and diseases (47.5%).

The barriers limiting the accessibility of the preferred yam varieties are presented in Table 5. The result shows that the high cost of the preferred yam varieties makes it inaccessible for farmers from the four regions under study in the following order: SE (30.2%), SS (61.0%), SW (63.5%), and NC (83.3%). Non-availability is seen as a barrier limiting the accessibility of preferred yam varieties, and this is observed in the following order: SS (11.3%), NC (17.2%), SE (18.6%), and SW (19.2%).

3.4. Socioeconomic factors influencing yam farmers' varietal selection decision across the study area

Table 6 shows the result of multinomial ordinal logistic regression of factors influencing yam farmers' decision in variety selection. The odds ratios of factors influencing yam farmer selection decision indicate that variables such as age, farm experience, access to credit, visit of extension agent, membership to yam association, and percentage income from the sale of yam influenced SE yam farmers' decision to select yam varieties that are big in tuber size, high in germination, and pest-free. The estimated coefficient of age and farming experience was found to have a positive and significant influence on yam farmers' selection decision criteria. This implies that the yam farmer unit change in age and farming experience will influence the decision to select a variety with big tuber size by 0.99 unit. The result further shows that the yam farmer's ability to select a variety with high germination rate was influenced by age and percentage income from the sale of yam. This result further indicates that a change in log odds ratio of 0.92 unit (age) and 0.99 unit (percentage income from yam) will influence a farmer's ability to select a variety with high germination rate. Our result shows that in SS Nigeria, yam farmers' decision to select a yam variety with high germination was determined by the total area cultivated with yam while selecting a yam variety with good tuber appearance was influenced by gender and percentage income from yam. The area under yam cultivation was found to have a significant influence on farmers' selection decisions. The log odds ratio in favor of selecting a variety with high germination rate increases by 0.98 units if a farmer accesses an additional hectare of land for yam cultivation.

Table 7 shows the result of the coefficient of odds ratios of factors that influences yam farmer selection decisions in SW and NC geopolitical zones of Nigeria. In the SW zone of Nigeria, the estimated coefficients of extension visits and access to loans influenced the decision to select the yam variety with good pounding attributes and early maturity. The ability of yam farmers in NC to select yam variety with big tuber size, good pounded attributes, and high germination rate could be determined by age, farming experience, membership of cooperatives, and total cultivated area.

4. Discussion

4.1. Farmers' preferred traits across gender and cultural patterns in Nigeria

To facilitate farmers' level of adoption of new yam varieties, understanding the criteria for varietal selection plays an important role and helps in guiding breeders and crop improvement experts (Fiacre et al., 2018). Farmers' trait preferences were similar across gender and geopolitical zones. Both male and female yam farmers considered variety with high germination rate, free from diseases, and having big tuber size in their selection decision. However, in SS and

TABLE 2 Distribution of respondents according to trait preference considered in yam variety selection decision by gender in South East and South South geopolitical zones of Nigeria.

Preferred trait	SE				SS			
	Male	Rank	Female	Rank	Male	Rank	Female	Rank
High germination or sprout emergence	1.24	1	1.38	3	1.29	2	1.44	2
High field establishment rate	1.49	14	1.62	15	1.43	13	1.48	6
Plant vigor (attractive growth)	1.39	5	1.49	10	1.30	3	1.52	8
Drought resistance	1.61	17	1.65	16	1.47	15	2.12	29
Tolerance to low soil fertility (grows well in all soil types)	1.41	7	1.38	4	1.37	9	1.64	16
Disease-free (clean leaves and vines with no visible disease)	1.42	10	1.27	1	1.37	10	1.4	1
High vegetation	1.72	22	1.92	26	1.72	25	1.76	22
Early maturity	1.36	4	1.65	17	1.39	11	1.44	3
Less likely to depend on staking (grow well under no staking)	2.09	27	2.19	27	2.23	28	2.32	30
Late maturity	4.01	31	4.30	31	3.13	31	3.4	31
Tuber yield	1.58	16	1.57	13	1.50	17	1.48	7
Tuber size	1.25	2	1.32	2	1.34	5	1.76	23
Tuber appearance (smoothness of skin)	1.48	13	1.54	11	1.41	12	1.56	10
Tuber shape	1.72	23	1.59	14	1.60	24	1.84	26
Tubers less susceptibility to deformation in soil (free from deformation)	1.93	25	1.86	24	1.51	20	1.64	17
Tubers free from diseases (rots)	1.51	15	1.41	6	1.34	4	1.44	4
Tubers free from pests (nematodes and scale insects)	1.26	3	1.44	9	1.35	7	1.52	9
Tuber flesh oxidation (non-browning or discoloration)	2.66	29	2.68	29	2.66	29	1.84	27
Tuber flesh color	1.65	18	1.54	12	1.60	23	1.6	13
Tuber firmness (higher dry matter an not too watery)	1.95	26	1.70	19	1.50	16	1.64	18
Cooking quality (fast cooking)	1.69	20	1.65	18	1.43	14	1.8	25
Pounded yam quality (taste, aroma, moldability, firmness, color, and stretchability)	1.39	6	1.41	7	1.28	1	1.56	11
Boiled yam quality (aroma, taste, firmness, mealiness, and color)	11.41	8	1.38	5	1.34	6	1.68	19
Fried yam quality (aroma, taste, and firmness/mealiness)	1.75	24	1.78	22	1.73	26	1.88	28
Peel loss	2.83	30	3.11	30	2.99	30	1.76	24
Tuber storability: long shelf-life or storage life without spoilage	1.42	11	1.76	21	1.35	8	1.44	5
Tuber dormancy (can stay long or short after harvest without sprouting)	2.31	28	2.35	28	1.81	27	1.6	14
Seed yam Hygiene (tubers clean or not)	1.67	19	1.81	23	1.51	18	1.72	20

(Continued)

TABLE 2 (Continued)

Preferred trait	SE				SS			
	Male	Rank	Female	Rank	Male	Rank	Female	Rank
Certified seed yam (seed yam certified or not)	1.71	21	1.89	25	1.59	22	1.72	21
Price of seed yam	1.45	12	1.70	20	1.56	21	1.6	15
Price of ware yam (marketability)	1.41	9	1.41	8	1.51	19	1.56	12
Kendall coefficient of concordance	0.3		0.749		0.551		0.633	
Value of *p*	0.0000		0.0000		0.0000		0.0000	

Computed from field survey 2021. SE, South East; SS, South South.

NC, the culinary quality trait, such as pounded yam attributes, was considered by male farmers from this region. It is exciting to observe that the *Tiv* and *Idoma* areas of the NC are among the major consumers of pounded yam which has a high cultural value in Nigeria (Nweke et al., 2013). The drivers of good pounded yam attributes including texture, mealiness, stretchability, and non-adhesiveness should be accorded high priority in selection and crop improvement strategies.

The female farmers from SS and NC selected a yam variety that matures early over late maturing ones. The majority of the respondents disclosed *via* personal communication that they would want the yam that could be harvested within 6 months because it will provide early food and cushion the food scarcity that is predominant within the cropping season pending harvest. A female respondent from Ikom, Cross River State highlighted that "beyond food provision for the family, yam farming provides an avenue to raise fund to address various family challenges." Musimbi (2007) had earlier identified early maturity as a trait usually considered by women when making varietal selection decisions. It, thus, suffices that yam product development will prioritize these gender dimensions within the product development stage. It is interesting to note that female farmers in NC and SE prefer yams with big tuber sizes because of their market appeal and ceremonial/cultural rites that go with big tuber sizes in the region. The big tuber size reduces the burden placed on these women to purchase sizeable products, especially during marriage ties of a close family member or children (Obidiegwu and Akpabio, 2017).

One of the gender-sensitive findings is the preference for tuber shape recorded among the female farmers from SW partly because women are actively involved in yam marketing and processing (Omojola, 2021). Thus, it becomes logical and demand-driven to develop gender-sensitive products that incorporate tuber size, high germination, disease-free, good shape, and early maturing with good pounded yam quality across diverse yam agroecologies in Nigeria.

4.2. Yam production constraints and accessibility of preferred varieties across the study zones

From this study, biotic and abiotic factors like pest/diseases attack, climate variability/change, and poor soil fertility were among the major challenges affecting the production of yam in the study areas. The attack of pests and diseases has been identified as a major constraint to yam production. Parasitic nematodes, fungi, and virus attacks, as well as leaf and tuber insects such as beetles, reduce tuber yield by 40% (Zaknayiba and Tanko, 2013). The variability in climate parameters significantly produces a changing pattern of rainfall and increased temperature across the different agroecological zones of Nigeria (Mondo et al., 2020). Agricultural practice in Nigeria is rainfed so rainfall anomalies will pose a great challenge to farmers. There has been a record of flooding in yam-producing regions such as the NC which resulted in the loss of farmland and farmers being displaced from their communities. Nigerian farmers have also experienced a series of drought events, which has caused physiological stress to field crops (Shiru et al., 2020). Diminishing soil fertility is what characterizes Nigerian soil due to intense farming activities. These barriers limit yam yield because most soil under yam cultivation in the NC and SE regions of Nigeria is observed to have reduced nitrogen, soil organic matter, and cation (Neina, 2021). The aforementioned challenges are well documented, but our study observed an increasing trend of drought spells, high rainfall patterns, declining soil fertility, and high cost of farm inputs occasioned by increasing inflationary trends in Nigeria.

This benchmark information drives the need to address biotic and abiotic stresses in the context of product profiling within the breeding programs. The direct and indirect drivers of traits should form the core of a scientific inquiry that will be built into the breeding pipeline so as to guide the development of products that can address the aforementioned biotic and abiotic challenges. It was affirmed by Nahanga and Vera (2015) that insufficient farm input serves as a constraint to yam production in developing countries like Nigeria, Ghana, Ivory Coast, Benin, and Togo. According to Bassey (2017), the cost of planting materials represents approximately 50% of the cost of yam production. It was further observed from the result that the non-availability of the preferred seed yams hinders them from reaching the farmers. The high cost of labor, weed infestation, staking, and high cost of seed yam also act as a barrier to yam production in the study area. The private seed sector, mainly driven by commercial and local seed entrepreneurs, has a strategic role in ensuring that certified seeds get to the farmers. This can be promoted by encouraging key investors in the formal seed system. Efforts need to be prioritized toward the development and standardization of technologies for high ratio propagation of high-quality breeder and foundation seed yams. The gaps in knowledge concerning pests (nematodes) and diseases (viruses and fungi) should be accorded prompt attention while developing sensitive and cost-effective management and diagnostics for major yam biotic challenges. Selecting non-stake bushy-type yams will significantly reduce the labor cost required for cutting, transporting, and placing stakes as well as reducing the burden of trailing yam vines onto stakes.

TABLE 3 Distribution of respondents according to trait preference considered in yam variety selection decision by gender in South West and North Central geopolitical zones of Nigeria.

Preferred trait	SW				NC			
	Male	Rank	Female	Rank	Male	Rank	Female	Rank
High germination or sprout emergence	1.14	2	1.13	1	1.13	3	1.18	5
High field establishment rate	1.22	5	1.27	7	1.25	12	1.18	6
Plant vigor (attractive growth)	1.43	13	1.47	14	1.27	13	1.45	13
Drought resistance	1.57	18	1.53	16	1.41	19	1.64	18
Tolerance to low soil fertility (grows well in all soil types)	1.87	23	2.27	29	1.73	26	1.68	20
Disease-free (clean leaves and vines with no visible disease)	1.87	24	2.00	24	1.78	28	1.55	16
High vegetation	1.35	10	1.20	4	1.40	18	1.68	21
Early maturity	1.11	1	1.20	5	1.20	5	1.14	2
Less likely to depend on staking (grow well under no staking)	1.46	14	1.47	15	1.90	29	2.45	29
Late maturity	2.71	31	2.47	31	3.62	31	3.45	31
Tuber yield	1.88	25	2.00	25	1.23	9	2.05	27
Tuber size	1.14	3	1.40	11	1.09	1	1.09	1
Tuber appearance (smoothness of the skin)	1.37	11	1.27	8	1.21	8	1.23	7
Tuber shape	1.35	9	1.13	2	1.34	14	1.50	14
Tubers with less susceptibility to deformation in soil (free from deformation)	1.88	26	1.93	22	1.50	21	1.62	17
Tubers free from diseases (rots)	1.54	17	1.93	23	1.20	7	1.36	11
Tubers free from pests (nematodes and scale insects)	1.60	19	1.73	20	1.23	10	1.32	9
Tuber flesh oxidation (non-browning or discoloration)	1.65	20	1.33	9	1.61	22	2.09	28
Tuber flesh color	1.47	15	1.33	10	1.62	23	1.82	25
Tuber firmness (higher dry matter and not too watery)	1.88	27	2.00	26	1.68	25	1.77	24
Cooking quality (fast cooking)	1.31	8	1.40	12	1.36	17	1.50	15
Pounded yam quality (taste, aroma, moldability, firmness, color, and stretchability)	1.14	4	1.20	6	1.10	2	1.14	3
Boiled yam quality (aroma, taste, firmness, mealiness, and color)	1.39	12	1.53	17	1.25	11	1.32	10
Fried yam quality (aroma, taste, and firmness/mealiness)	1.72	21	1.60	18	1.49	20	1.68	22
Peel loss	2.08	28	2.00	27	2.04	30	2.50	30
Tuber storability: long shelf-life or storage life without spoilage	1.22	6	1.40	13	1.15	4	1.14	4
Tuber dormancy (can stay long or short after harvest without sprouting)	2.28	30	2.40	30	1.62	24	1.82	26
Seed yam Hygiene (tubers clean or not)	1.51	16	1.73	21	1.35	16	1.68	23
Certified seed yam (seed yam certified or not)	2.11	29	2.20	28	1.76	27	1.64	19
Price of seed yam	1.83	22	1.67	19	1.34	15	1.36	12
Price of ware yam (marketability)	1.28	7	1.13	3	1.20	6	1.27	8

(Continued)

TABLE 3 (Continued)

Preferred trait	SW				NC			
	Male	Rank	Female	Rank	Male	Rank	Female	Rank
Kendall coefficient of concordance	0.643		0.569		0.715		0.692	
Value of *p*	0.0000		0.0000		0.0000		0.0000	

Computed from field survey 2021. SW, South West; NC, North Central.

TABLE 4 Constraints affecting yam farmers across agroecology in Nigeria.

Constraints	NC (%)	SE (%)	SS (%)	SW (%)
Climate change	16.25	27.5	11.25	61.25
Cost of seed yam	8.75	13.75	1.25	2.5
High cost of farm inputs	72.5	11.25	18.75	10
High cost of labor	22.5	25	18.75	16.25
Insecurity	17.5	1.25	0	5
Lack of improved seeds	5	7.5	7.5	1.25
Low sprouting	8.75	0	5	17.5
Low yielding	10	10	2.5	5
Pest/disease attacks	47.5	56.25	50	33.75
Poor soil fertility	45	10	17.5	3.75
Staking	2.5	5	11.25	0

SE, South East; SS, South South; SW, South West; NC, North Central.

TABLE 5 Constraints in accessing preferred yam varieties.

Factors	NC (%)	SE (%)	SS (%)	SW (%)
High cost	83.3	63.5	61.0	30.2
Lack of information	0.6	1.9	1.9	2.3
Market distance	4.0	0.6	4.4	2.9
Never seen improved seed	0.6	0.0	9.4	0.0
No constraint	6.3	2.6	2.5	2.3
Non-availability	17.2	18.6	11.3	19.2

SE, South East; SS, South South; SW, South West; NC, North Central.

5. Conclusion

This study provides information on farmers' preferred traits as well as constraints limiting yam production. The wealth of information generated forms a good foundation for cross-cutting considerations and policy interventions in yam crop improvement system. The identified factors responsible for influencing farmers' decision to select yam varieties with preferred traits are age, farm experience, access to credit, visit of extension agents, membership to yam association, percentage income from the sale of yam, extension visit, and access to loan. The SE and SS yam farmers prefer yam varieties with big tuber size, high germination rate, no pest issue, and good tuber appearance. While farmers in SW and NC desire good pounding quality and early maturity, other important traits to be considered within the breeding programs include tuber storability, high field establishment, and tolerance to low soil fertility. The adoption of yam varieties can be improved through access to loans, regular visits by extension agents, and regular training of yam farmers. Strengthening the capacity of key service providers in national extension, advisory services, and non-governmental organizations (NGOs) through training will ensure that not only significant numbers of beneficiaries are reached but also that it will provide the opportunity for future sustainability and scalability. Regular participatory research activities and market intelligence updates with value chain actors will further strengthen the adoption of breeding innovations while providing the basis for achieving wide-scale impact.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the

TABLE 6 Odds ratio of factors influencing yam farmers' variety selection decision in South East and South South Nigeria.

Variable	SE			SS		
Odds ratios	Tuber Size	High Germination	Pest-Free	High Germination	Tuber Size	Tuber Appearance
Sex	1.14	1.42	1.92	2.77	2.86	1.66**
Age	0.99*	0.92*	0.96	0.95	0.96	0.98
Level of education	1.03	0.96	0.98	1.06	1.01	0.99
Farming experience	0.99**	1.04	0.99	1.07	1.03	0.98
Visit of extension agents	2.11	0.35	0.24	0.41	0.57	0.46
Access to credit	0.30*	2.58	0.83**	0.81	6.45	2.71
Accessed loan	0.37	0.49	1.25	2.32	0.73*	1.61
Member of yam association	0.14	1.41	0.51*	0.75*	1.26	2.14
Received training	0.18	1.00	0.75	2.58	0.21*	0.22
Total land owned	0.98	1.01	0.77	1.02	0.95	0.99
Total cultivated	1.03	0.96	1.21	0.98***	0.90	0.95
Years of yam farming experience	1.05	1.04	1.05	1.00*	1.02	1.04
Percentage of income from sale of yam	0.98	0.99*	1.08	0.99	1.00	0.99*
Log likelihood	−82.72	−80.70	80.52	−96.13	−114.16	−117.20
Value of *p*	2.8e-03	2.44e-12	6.84e-07	2.6e-13	1.1e-09	4.05e-13
N	142	142	142	159	159	159

*10 percent level of significance, **5 percent, and ***1 percent. SE, South East; SS, South South; N, Sample size.

TABLE 7 Odds ratio of determinants of factors influencing yam farmers' variety selection decision in SW and NC Nigeria.

Variable	SW			NC		
Odds ratios	Pounded yam quality	Early maturity	High Germination	Tuber size	Pounded yam quality	High Germination
Sex	1.92	2.28	0.74	0.54	1.63	1.60
Age	0.95	1.05	1.06	1.04	1.00*	1.05
Level of education	1.07	1.04	0.93	0.97	1.03	1.00
Farming experience	1.08	1.00	0.96	0.96*	1.00	0.99**
Visit of extension agents	0.59*	2.40	1.46	3.87	1.18	0.68
Access to credit	3.00	2.47	0.41	1.97	2.20	6.38
Accessed loan	0.99	0.51**	1.54	1.39	3.01	0.52
Member of yam association	0.19	1.59	0.72	0.27***	0.55	0.59
Received training	1.71	0.45	0.47	0.96	0.87	0.36
Total land owned	0.96	0.90	1.00	0.95	1.02	1.01
Total cultivated	1.02	0.98	0.96	0.81	0.84**	0.86
Years of yam farming experience	1.00	1.00	1.00	1.00	1.01	0.95
Percentage of income from sale of yam	1.00	0.98	0.97	0.98	0.98	1.00
Log likelihood	−52.81	−44.85	−58.48	−67.45	75.81	−78.01
Value of *p*	4.6e-09	4.7e-11	2.8e-08	3.8e-08	2.7e-05	7.3e-13
N	163	163	163	250	250	250

SW, South West; NC, North Central; N, Sample size.

participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

AA and JO conceptualized the study idea. CK, IN, AE, PAA, and JO took part in the survey study. AA, JO, PAA, and PA coordinated the data generation. CK, IN, and JO analyzed the data and wrote the first draft with inputs from AA, PA, and PAA. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1227920/full#supplementary-material

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EDITED BY
Subhash Babu,
Indian Agricultural Research Institute (ICAR), India

REVIEWED BY
Sanjit Maiti,
National Dairy Research Institute (ICAR), India
Souvik Ghosh,
Visva-Bharati University, India

*CORRESPONDENCE
Rupak Goswami
✉ rupak.goswami@gm.rkmvu.ac.in

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Resource interaction in smallholder farms is linked to farm sustainability: evidence from Indian Sundarbans

Rupak Goswami[1,2,3]*, Sonja Brodt[4], Sangita Patra[1], Purnabha Dasgupta[1], Biswanath Mukherjee[3,5] and Somen Nandi[2,3]

[1]Integrated Rural Development and Management Faculty Centre, Ramakrishna Mission Vivekananda Educational and Research Institute, Kolkata, India, [2]Department of Chemical Engineering, University of California, Davis, Davis, CA, United States, [3]Global HealthShare® Initiative, University of California, Davis, Davis, CA, United States, [4]University of California Sustainable Agriculture Research and Education Program, Davis, CA, United States, [5]Department of Computer Science, University of California, Davis, Davis, CA, United States

Efficient resource utilization in small-scale farms is crucial to achieving farm sustainability through endogenous mechanisms. However, the precise mechanisms to integrate farm resources to achieve farm sustainability are not very clear yet. By capturing the interaction among farm resources as a network phenomenon, we aimed to identify the discrete resource interactions (RIs) associated with higher farm sustainability in different farm types of Indian Sundarbans. First, we assessed the sustainability of 140 integrated farms using a synthesized assessment framework. Then, we considered four network motifs, namely linkage (a one-way link between two resources), reciprocal linkage (a two-way link between two resources), triad (three resources having closed interconnectedness), and the presence of a farm resource at the core of a network. Using RI network data of 140 farms and employing a graph theoretic approach we identified discrete network motifs (i.e., resource interaction) associated with highly sustainable farms in different farm types. We found a predominance of rice, vegetables and pond-based integration and identified 32 linkages, 11 reciprocal linkages, 21 triads, and three resources at the network core that occurred and co-occurred on highly sustainable farms, and thus critical to achieving farm sustainability. Further, multivariate analyses established that the properties of RI networks could explain farm sustainability significantly. We anticipate that sustainability in small-scale farms can be achieved by strategically designing new RIs on the farm. However, there may be limitations to such achievement depending on the nature of RI and the type of farm.

KEYWORDS
resource integration, network analysis, sustainability, farm typology, small-scale farm

1. Introduction

Nearly 2.5 billion small-scale farms operate on 60 per cent of the world's arable lands, and their sustainability is critically important to meet the growing demand for food in the coming decades (Cui et al., 2018; Guiomar et al., 2021). These farms, across the globe, are typically characterized by resource-poor conditions, vulnerability to biotic and abiotic stresses, climatic variability, and structural constraints (Altieri et al., 2012) and needs strategic intensifications to improve their food-income-energy-natural resource nexus

(Gathala et al., 2020, 2021). Achieving sustainability in this large number of small farms will not only play an essential role in ensuring global food and nutritional security (Cui et al., 2018; Brunori et al., 2020; Giller et al., 2021) but also present a means to secure inclusive economic growth, reduce the vulnerability of rural communities, and rapidly reduce poverty (Apata et al., 2020; Gomez y Paloma et al., 2020). Since small-scale farms often cannot access the same external resources as well-off farms, the existing resources on small farms must be used strategically to move toward sustainability, irrespective of external interventions. Thus, it is crucial to examine how decisions to use a set of available farm resources affect its sustainability.

The speed of exit from smallholder systems remains slow in many developing countries, and increasing population pressure on these systems may lead to resource degradation and reduced efficiency in the long run (Hazell and Rahman, 2014). Both the ideas of "sustainable intensification" (SI) (Rockström et al., 2017; Cassman and Grassini, 2020) and "ecological intensification" (EI) (Tittonell, 2014a; MacLaren et al., 2022) evoke that productivity and sustainability can be synergistic, rather than merely needing to strike a balance between the two (Pretty et al., 2018). For the past few decades, examples of sustainable forms of intensification have shown promise in both developed and developing countries (Pretty and Bharucha, 2014; Jat et al., 2020) and emerged as alternative ways of farming (Wezel et al., 2014). However, the mechanisms of SI have been summarized only recently (Pretty et al., 2018; Cassman and Grassini, 2020; Kuyah et al., 2021), and understanding the pattern to combine existing farm resources (referred to as resource interaction in this article) as a means of SI remains an outstanding issue.

Sustainable forms of intensification may be achieved by either increasing efficiency, substituting new technologies and practices, or redesigning the way a system functions (Hill, 1985). It is argued that the conscious designing of farming systems can be a strategy for smallholder farmers to achieve sustainable livelihoods (Tittonell, 2014b; Goswami et al., 2016; Andrieu et al., 2019). We posit that farm families can negotiate multiple factors, internal and external to the farming systems, and consciously design and readjust the farm resources to achieve short- and long-term sustainability. Attributing such resource interactions (RI) with farm sustainability can enhance our ability to design farming systems for strategic gains in smallholder sustainability. By RI we refer to human-managed material and energy flow and space sharing between different farm components such as land, water bodies, livestock, and vegetation. Farm components are physical entities that host the resources and their interactions.

The existing systems analytic approaches in agriculture have advanced our understanding of how farming systems function (Roling, 1991; Collinson, 2000; Hall et al., 2003; Temel et al., 2003; Spielman et al., 2011; Holzworth et al., 2015; Schut et al., 2015; Basso et al., 2016; Jones et al., 2017), but linking discrete SI with multiple outcomes in farming systems is extremely limited (Musumba et al., 2017; Li et al., 2020). By capturing the interaction among farm resources as a network phenomenon, we aimed to identify the discrete RIs associated with higher farm sustainability in different types of 140 small-scale farms in the Indian Sundarbans. Also, we linked farm sustainability with the network properties of farm RI in different farm types. The analyses may open up the study of agricultural systems from a network perspective and encourage researchers to find discrete RI "motifs" for an informed design of farming systems, something analogical to the genetic code of sustainable agricultural systems.

2. Methods

2.1. Sampling and locations

Enumerators collected the field data from farms in selected areas of Indian Sundarbans, which are constituted of 19 community development blocks (CDB) (Supplementary Figure S1). We randomly selected one CDB each from 13 CDBs of South 24 Parganas district and six CDBs of North 24 Parganas District in the West Bengal State of India. From each CDB, we selected one Gram Panchayat (GP) (village self-governing body) randomly. Fifty-two farms from the selected GP of South 24 Parganas and 88 farms from the selected GP of North 24 Parganas representing nearly 15% of the farm families in those GPs—were randomly selected from a list of farms prepared in consultation with the local stakeholders of agricultural development. We selected farms below the size of two ha to maintain a normative classification of the agricultural census. But, because of the extremely small size of farms, all farms (except for two) were less than one hectare in size.

There are six agro-climatic zones—based on climate, soil, and physiography—in the state of West Bengal in India, and the Sundarbans region comes under the coastal saline zone (Gajbhiye and Mandal, 2000). The Indian part of Sundarbans consists of 4,200 km^2 of reserved forest and 5,400 km^2 of non-forest areas, and it is intersected by large numbers of rivers, rivulets, and tidal waterways. Fifty-four islands are inhabited by over 4.4 million people (World Bank, 2014). River embankments guard the boundaries of islands in the upstream areas, but tidal saline water often intrudes into the embankments and floods farmlands. Soil salinity increases in dry months to render the soil uncultivable. The region is vulnerable to cyclonic storms and prolonged inundation. Rice is the main crop grown over different land terrains and seasons. Spring paddy, sesame, and green gram in the early wet season; jute and *aman* rice in the wet season; maize, different oilseeds and pulses; and vegetables in the winter season are the important crops. Apart from agriculture, a large portion of the population depends on non-timber forest products and migrates to urban centers of India and abroad. Population density has risen rapidly over the past decade and is well above the national and state average. Sustainable use of natural resources is critical to managing livelihoods in the region. Nearly half of the region's population live below the poverty line, and limited employment opportunity creates conflict between livelihoods and environmental sustainability. Nearly all farmers are living marginally, having less than one hectare of land, and sustaining households using small parcels of land within the context of socioeconomic; environmental vulnerability is a great challenge to support smallholders in Sundarbans.

2.2. Data

We collected field data through face-to-face interviews with a pre-tested standardized interview schedule (RKMVERI/NDP/EC/RG/Fulb/2018-19) and farm-level measurements. The interview schedule consisted of respondents' background information, livelihood assets, household income and expenditure, details on farming practices, and resource interaction on the farm. The data collection instrument had all the sustainability assessment indicators. The draft instrument was piloted on non-sampled integrated farms in the study areas and modified based on piloting experience. The enumerators stayed in the villages before collecting data, and the actual field data were collected on 140 farms from March-June 2018. Observations and measurements were made on the farms during the interview itself. Summarily, we collected field data to (a) delineate farm types and characterize them, (b) assess the farm's sustainability, and (c) assess farm resource interaction.

2.3. Typology delineation

Since the smallholder system is heterogeneous in terms of evolution, resource endowments, and vulnerabilities, the smallholder farmers are expected to employ different resource intensification strategies and might pursue different trajectories of sustainability outcomes (Tittonell, 2014b). Different types of farms employ different mechanisms of RI to achieve sustainable livelihoods. Hence, typology delineation for small farms is a pragmatic step to simplify the diverse farming systems before studying the interrelationship of RI and farm sustainability. Based on representative literature (Netting, 1993), we selected 18 potential indicators (Supplementary Table S1) to define the smallholder system in the study region. To reduce the multicollinearity of the data, we used principal component analysis (PCA) to extract six principal components (PCs). These PC scores were then used in hierarchical cluster analysis and K-means cluster analysis to arrive at five distinct farm types (Supplementary Tables S2–S4). Once we classified the farms based on these six PCs, we characterized them in terms of a set of background variables (Supplementary Table S5). We tested whether the five farm types differed in terms of this set of background variables. Significant variables in the one-way ANOVA and Chi-square tests suggested the efficacy of our classification. For quantitative variables, we used *post-hoc* tests after the one-way ANOVA to identify the distinctly high or low farm types for the individual variables (Supplementary Table S6). Mostly, these distinct high and low values of indicators were used to characterize different farm types. When the mean value of a variable for a farm type was highest and significantly higher than the other farm types in the *post-hoc* test, we called it "high". Similarly, the statistically significant lowest value of a variable was called "low". Anything in between was called "moderate". A qualitative description of the delineated farm types is given in Supplementary Table S7.

2.4. Sustainability assessment

To assess smallholder farms' sustainability, we scouted a suite of indicators following relevant assessment frameworks of local and global importance (Scoones, 1998; Rao and Rogers, 2006; FAO, 2014; Goswami et al., 2017). Our framework is grounded on the sustainable livelihoods framework and guided the selection of indicators (Supplementary Figure S2), the coverage of social, economic, and ecological dimensions of sustainability, access and availability of related data sources, cost of measurement, time involved, and understanding of the indicator by the respondents (Dasgupta et al., 2017). Thus, we identified 39 indicators covering social (16), economic (12), and ecological (11) dimensions of sustainability (Supplementary Table S8). We incorporated these 39 indicators in a data collection instrument and pre-tested them on non-sampled integrated farms before the final data collection on 140 integrated farms. These indicators were standardized using max-min standardization, winsorized (to manage outliers), weighted, and aggregated to develop a composite sustainability index (SI) (OECD, 2008; Goswami et al., 2017). We employed principal component analysis on the dataset and used factor loadings of the principal components for weighing individual indicators. Finally, we aggregated the weighed indicators linearly to develop a composite sustainability index. The index value ranged from 0 to 100, "0" being the lowest and "100" being the highest possible value (Supplementary Section S3; see Supplementary Table S9 for comparison of sustainability indicators across farm types).

2.5. Network data for studying farm resource interaction

Farm families of the study locations identified 10 types of distinct resources/farm components, namely Rice field (R), Vegetable plots (V), Cattle (C), Poultry (PL), Pond (PN), Homestead (H), Tree (T), Kitchen (K), Common property resources (CP), and Fallow land (F) before the actual data collection. We considered the presence of a resource interaction (RI) on the farm when a perceived flow of energy or matter or sharing of space between any two of these 10 resources existed. We ascertained such existence in consultation with the respondents coupled with farm visits and measurements. We recorded the RI in a 10x10 binary matrix for all 140 farms. Thus, there were 140 RI networks and 140 binary matrices. In graph-theoretic parlance, a node in the RI network represents a resource/farm component, and a directed tie represents the interaction between two nodes. Based on the matrices, we generated two types of network information for individual farms: First, we identified the linkage, reciprocal linkage, triads, and presence of a resource/farm component at the core of the RI network (Borgatti and Everett, 2000) to understand the structural composition of the farm resource interaction. Second, we computed different network properties of individual farms, namely density, component ratio, connectedness, fragmentation, compactness, dependency ratio, Weiner index, closure, transitivity, clustering coefficient, and arc reciprocity, to understand the nature of resource interaction in the farms (Supplementary Table S10).

We used UCINET for Windows software (Borgatti et al., 2002) for matrix manipulation and analyses of the farm RI's structural composition, i.e., the ties, reciprocal ties, triads, and presence at the core. We used the same software for the computation of the network properties of RI. The structural compositions were then related to farm sustainability and farm types in a graph-theoretic layout using NetDraw software (Borgatti, 2002). NetDraw was also used for the visualization of the co-occurrence of RI.

2.6. Linking network analysis with farm sustainability

We examined the relationship between RI and farm sustainability following two approaches. First, we developed a two-mode network (network involving both the resources and individual farms) of 140 RI networks and visualized it in the graph-theoretic layout. This helped to identify the RI motifs associated with highly sustainable farms. Then, to study the co-occurrence of RI motifs on individual farms we converted the two-way networks into one-way networks (considering RI motifs as the nodes) and visualized them in a metric multi-dimensional layout. The proximity of RI motifs denoted their higher tie strength and thus a higher probability of co-occurrence. The RI motifs that were associated with highly sustainable farms and co-occurred on the same integrated farms were identified as the critically important motifs for achieving farm sustainability.

Second, we used two extracted principal components from 11 network properties of 140 farms to explain their sustainability score (Supplementary Tables S11, S12). Using SPSS Modeler 18.1 (IBM_Corp, 2016), we employed 12 models together, and the output is based on the three best-performing models in terms of their correlation value and relative error (Supplementary Table S13). The relationship was also examined separately for all five farm types to examine whether it held across farm types.

3. Results

3.1. Farm typology

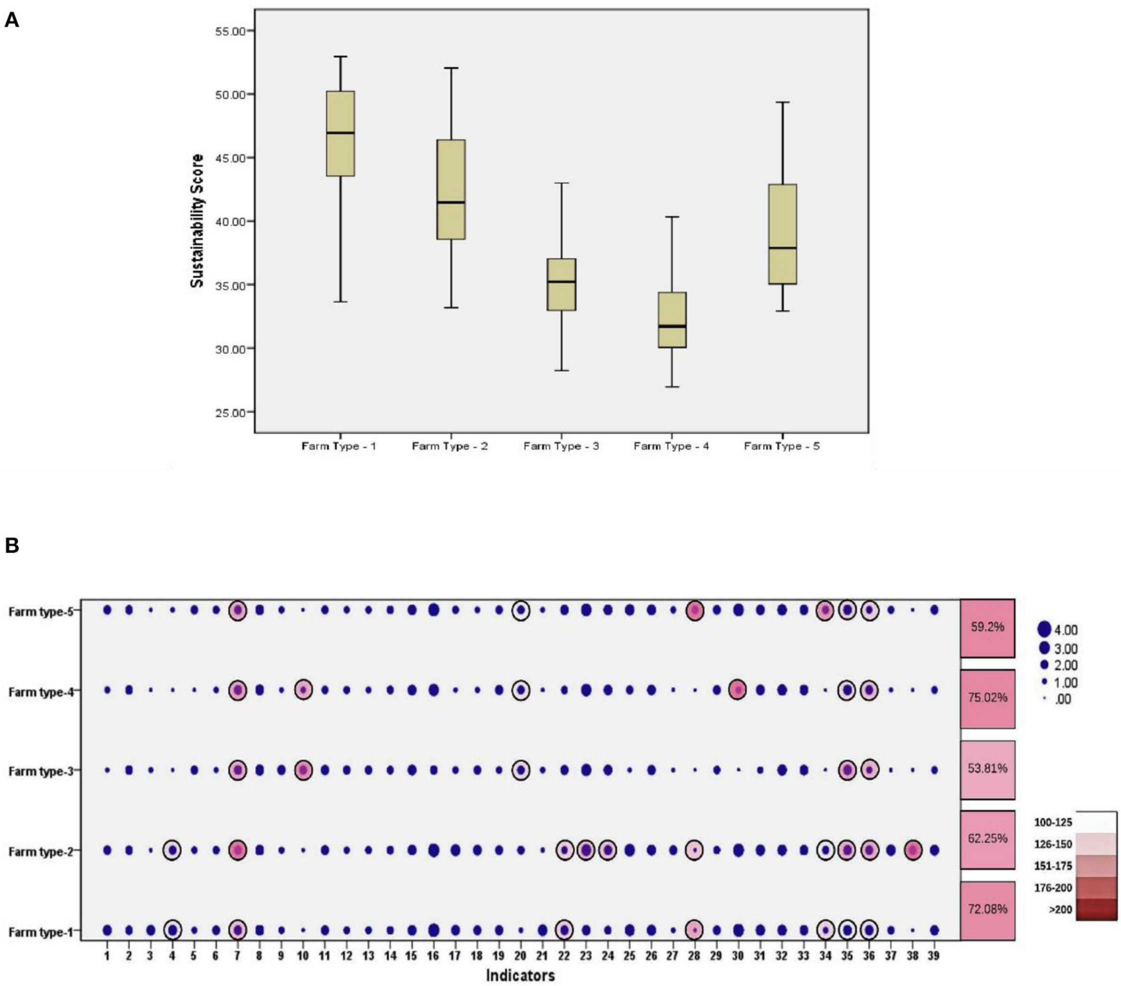
We identified five farm types using a sequence of principal component analysis (PCA) and hierarchical cluster analysis (CA) to reduce the heterogeneity of smallholder systems and created socio-ecological boundaries within which resource management could be understood better (Kansiime et al., 2018) (Supplementary Information details the typology delineation and characterization in Supplementary Tables S1–S6, Supplementary Sections S1, S2). Farm type-1 (22 no., 15.71% of farms) were resource-rich extended families who employed low-to-moderate input intensity and demonstrated moderate-to-high system yield and system profitability in their farms. Farm type-2 (28 no., 20% of farms) were resource-poor extended families, who achieved high system yield by employing high input intensity and family labor. Farm type-3 (33 no., 23.57% of farms) were resource-poor feminized subsistence farms that diversified with livestock and non-farm incomes, used low input intensity in farming, and received moderate system yield and low system profitability. Farm type-4 (35 no., 25% of farms) was predominated by resource-poor and marginalized tribal nuclear families, who survived on off-farm wages, used low input intensity on their farms, and achieved moderate system yield and low system profitability. Farm type-5 (22 no., 15.71% of farms) was resource-poor, profit-oriented nuclear families, which diversified with livestock, earned little or no off-farm income and employed moderate management intensity to maintain moderate system yield and profitability. A summarized qualitative description of farm types is given as Supplementary Information (Supplementary Figure S3; Row 1, Supplementary Table S7).

3.2. Farm sustainability and its drivers in the study areas

We assessed the sustainability of 140 farms by a composite index built on 39 indicators covering social, economic, and ecological dimensions of sustainability (Supplementary Table S8). The mean sustainability score for FT-1 was highest, followed by FT-2, FT-5, FT-3, and FT-4 (Figure 1A). The resource-rich large families (FT-1) fared better than other farms in terms of multifunctionality, balanced soil reaction, contact with extension functionaries, lower cost of production, availability of cereals, and adoption of sustainable agricultural practices (Figure 1B). FT-2 closely followed FT-1 in all the above indicators and came next to highest in terms of women's engagement as family labor, family dependency ratio, women's access to farm resources, use of family labor in farming, lesser soil salinity, tree species diversity, per-capita income, the proportion of irrigated land, system profitability, use of organic manure, and rice equivalent yield. FT-5 followed FT-1 or FT-2 in terms of several indicators and emerged next to the highest in livestock index and distance to the road. FT-3 fared best in terms of Nitrogen, Phosphorus, and Potassium (NPK) use, pesticide use, distance to market, access to financial institutions, use of indigenous knowledge and per-capita food availability, apart from being second best in terms of livestock index, training, availability of cereals, and soil fertility. FT-4 fared well in terms of income diversity and soil fertility; they emerged second best in terms of distance to market, NPK use, pesticide use, and use of indigenous knowledge. An explanatory note on the rationale of abovesaid characterization (Supplementary Section S2, Supplementary material) and a summarized description (Row 2, Supplementary Table S7) are given as Supplementary material. An explanatory scheme shows sustainability regimes of different farm types concerning their assets and capabilities for a better comprehension of the readers (Supplementary Figure S4).

3.3. The abundance of farm resource interaction

We examined the abundance of four types of RI motifs, namely linkage, reciprocal linkage, triad, and presence (of a resource) at the core (see definitions in Supplementary Table S10) in five identified farm types (Figure 2) to characterize them in terms of these interactions. The heatmap cells represent the proportion



Indicator code: 1-Experience of farming, 2-Family dependency ratio, 3-Land holding, 4-Homestead land, 5-Livestock index, 6-Social participation, 7-Training, 8-Availability of cereals, 9-Dietary diversity, 10-Per-capita food grain, 11-Women's access to farm resource, 12-Use of indigenous knowledge, 13-Pride of being a farmer, 14-Use of family labor in farming, 15-Gendered use of family labor, 16-Multifunctionality of farming, 17-Total income, 18-Per-capita income, 19-Income diversity, 20-Proportion of irrigated land, 21-Cultivated land, 22-Access to financial institutions, 23-Distance to market, 24-Distance to road, 25-Extension contact, 26-System cost of cultivation, 27-System profitability, 28-Investment in farm, 29-Soil fertility, 30-Soil reaction, 31-Soil salinity, 32-NPK use, 33-Pesticide use, 34-Organic manure use, 35-Ownership of pond, 36-Irrigation by preserved water, 37-Tree species diversity, 38-Rice Equivalent Yield (REY), 39-Adoption of good agricultural practices

FIGURE 1
(A) Sustainability score of farms under five farm types. Sustainability is assessed by a composite sustainability index developed from 39 indicators (Supplementary Table S3). The indicators are normalized, winsored, weighted and linearly aggregated to develop the composite index. **(B)** Performance of different farm types in terms of 39 sustainability indicators. Indicator scores are standardized weighted values. Circles are scaled by indicator scores. Encircled dots have higher variability (>100% CV) within a farm type, and the deeper colors represent high variability. Boxes at the extreme right show indicator-level variation (average CV% of 39 indicators), deeper colors being more variable. Larger dots, which are not encircled, are considered more stable and used to characterize farm types.

of farms under individual farm types having a specific RI motif. Both FT-1 and FT-2 are characterized by R- (Rice->Cattle), H- (Homestead->Tree), and V (Vegetables->Poultry) based linkages, R-based reciprocal linkages (Rice<->Cattle), R- and V-based triads (ΔRice<->Cattle<->Homestead), and presence of R and V (R, V, and C for FT-2) at the core of RI network. Although the abundance of RI is similar in FT-1 and FT-2, the difference primarily exists in the magnitude of their abundance. Also, in FT-2, the importance of C and the use of CP and F are unique. Unlike FT-1 and FT-2, FT-3 is characterized by linkages

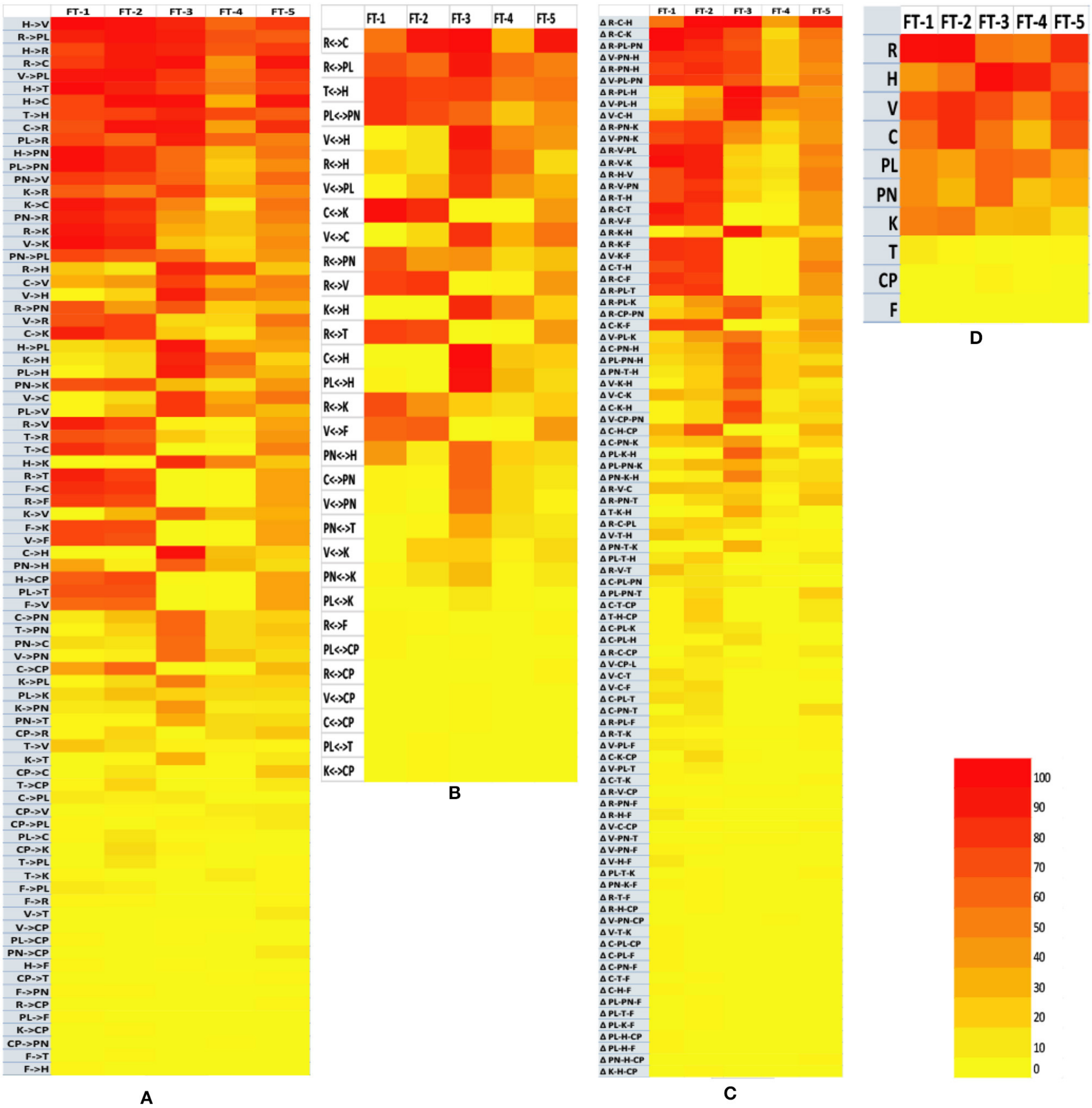


FIGURE 2
Abundance of different types of resource interaction motifs across farm types—**(A)** Tie/linkage; **(B)** Reciprocal tie/linkage; **(C)** Triad; and **(D)** Presence in the core. Abundance indicates the percentage of farms having a type of resource interaction within a given farm type.

involving diverse resources such as R, H, V, PL, PN, and C; predominantly H, PL, PN, and V-based reciprocal linkages; R, V, PN, PL, and H-based triads; and the presence of H and V at the core of the RI networks. FT-4 shows fewer linkages, reciprocal linkages, and triads, and features the presence of H at the core of the networks. FT-5 is characterized by a smaller number of diverse linkages involving R, H, and C, very few reciprocal linkages and triads, and the presence of R, V, and C at the core of the RI networks. Overall, FT-1 and FT-2 employed similar resource integration strategies centering around R, H, and V, with FT-2 integrating C and V slightly more than FT-1. FT-3 used diverse resources for interaction—centering around H—that could spatially accommodate V, PN, PL, C, and K due to their physical proximity. For FT-4, the paucity of resources and dependence on off-farm income might have resulted in a lack of resource interaction on their farms. FT-5, on the other hand, showed a diverse but non-predominant nature of resource interactions centering on rice fields (R), homesteads (H), and cattle (C) (see Row 3, Supplementary Table S7 for a typology-wise detailed description).

3.4. Farm resource interaction linked to farm sustainability

We examined the relationship of RI with farm sustainability by examining the proximity of discrete RI (squares) with the sustainable farms (larger circles, area scaled by farm sustainability score) in a graph theoretic layout of the two-mode RI-farm network (see Supplementary Figures S5a–S5d; an explanatory description is given in Section S4) and identified the discrete RI associated with highly sustainable farms (Row 4, Supplementary Table S7). Scrutiny of the farms in the ninth decile of the sustainability score provided a hint of how the highest sustainability was achieved, irrespective of farm types, by using specific RI motifs and not others (Figures 3A–D; Row 1, Table 1). Scrutiny of Row 1 in Table 1 and Row 4 in Supplementary Table S7 (and Figures 3A–D and Supplementary Figures S5a–S5d) shows a high commonality of RI associated with sustainable farms. This indicates that higher sustainability was achieved by a small number of unique RI motifs in individual farm types. Summarily, we found that farms achieved higher sustainability by having R-, V, C-, PN-, PL-, H-, and K-based linkages; R- and PN-based reciprocal linkages; R-, V-, PN-, K-, and H-based triads; and presence of R, V, C, K, PN, and PL at the core.

3.5. Co-occurrence of farm resource interaction

We also studied the co-occurrence of RI motifs, meaning the simultaneous occurrence of RI motifs on the same farm. We performed the co-occurrence study for two reasons—first, the co-occurrence of resource interaction on a farm is expected to be more stable because of its possible interdependence tested by the farmers. Hence, studying them gives us an idea of what RIs go together and stabilize in smallholder systems of a region as a response to the internal and external stimulus of change to the farming systems. Second, in the absence of panel data on farm RI or empirical study on the evolution of regional farming systems, the study of the co-occurrence of RI motifs could suggest the possible evolutionary stage of RI in smallholder systems. Despite the limitation of snapshot data, we can still examine how these co-occurrence patterns of RI gravitated toward highly-sustainable farms. We segregated the co-occurrence of RIs for farms of the ninth decile of sustainability (Figures 4A–D; Row 2, Table 1). These farms, irrespective of their farm types, featured 35 co-occurring linkages, 11 co-occurring reciprocal linkages, 28 co-occurring triads, and the presence of R, V, and PN at the core in terms of their high tie strengths (Row 2, Table 1). This means that these RIs are more closely linked and likely to co-occur on the same farm to achieve high farm sustainability. Summarily, we found that farms achieved higher sustainability by having R-, V-, C-, PN-, H-, PL- and K-based linkages; R- and PN-based reciprocal linkages; R-, V-, PN-, K-, and H-based triads; and presence of R, C, and K at the core. The co-occurrence network for all 140 farms is given as supplementary information (Supplementary Figures S6a–S6d). Notably, a high proportion of co-occurrences (recorded on 140 farms) are retained by the highly-sustainable farms of the highest decile.

Finally, we identified 32 linkages, 11 reciprocal linkages, 21 triads, and three core elements (Row 3, Table 1) that occurred and co-occurred in the highly sustainable farms (of the highest decile), and thus most critical to contribute to farm sustainability. Concrete examples of these critical RI motifs are given in Table 2.

3.6. Linking farm resource interaction with farm sustainability

We also explained the sustainability of the sampled farms by the properties of the individual farm's RI networks. We computed 11 network properties (Supplementary Table S10) for all the farms' RI networks and reduced their multicollinearity to two principal components (PC)—"connectedness" (PC1) and "reciprocity and transitivity" (PC2), and used them as the predictors of farm sustainability score. After examining 12 models, we found a model explaining 88.7% of the variance in farm sustainability scores (Figure 5A). We also examined how the model performs within different farm types (Figure 5B) and found the linear correlation for the five farm types to be 0.809, 0.715, 0.638, 0.727, and 0.86. These findings imply that resource interaction within a farm when expressed in terms of its network properties, can explain the farm sustainability measured by 39 multi-dimensional indicators, and this holds significantly true for all farm types.

We also examined the nature of this relationship at different values of PC1 and PC2 separately (Figures 6A, B). We found that farm sustainability increased monotonically with increased PC1 and found two areas of stacked points (farms) (Figure 6A), roughly the boundary of PC1 for one or more type/s of farms. While the first stack is the boundary of PC1 for FT-3 and FT-4, the second stack is the boundary for all other farm types. This indicated that RI, as a result of increased connectedness, could not be advanced by those groups of farms beyond a specific limit, although differential sustainability was achieved by farms of the same type with that same level of connectedness. These boundaries suggest a resource-limiting condition for a large number of resource-poor farms. We also found that PC2 enhanced farm sustainability up to a point and declined after that (Figure 6B). Here, also we find two stacks of farms—first, the highly-sustainable farms of FT-1, FT-2, and a few farms from FT-5; second, the poorly-sustainable farms of FT-3 and FT-4. We anticipate that highly-sustainable farms do not need to engage in many reciprocal and transitive RI on their farms since they could achieve substantial sustainability with one-way connectedness and do not need to move further toward the right of the x-axis. On the other hand, the second stack of farms has limited resources, which are located close to each other and easily linked resources (enhancing their reciprocity and transitivity). However, this could lift only a smaller proportion of farms above-median sustainability (Figure 6B).

4. Discussion

The study results suggested a suite of rice, vegetables and pond-based integration strategies for the integrated farms in

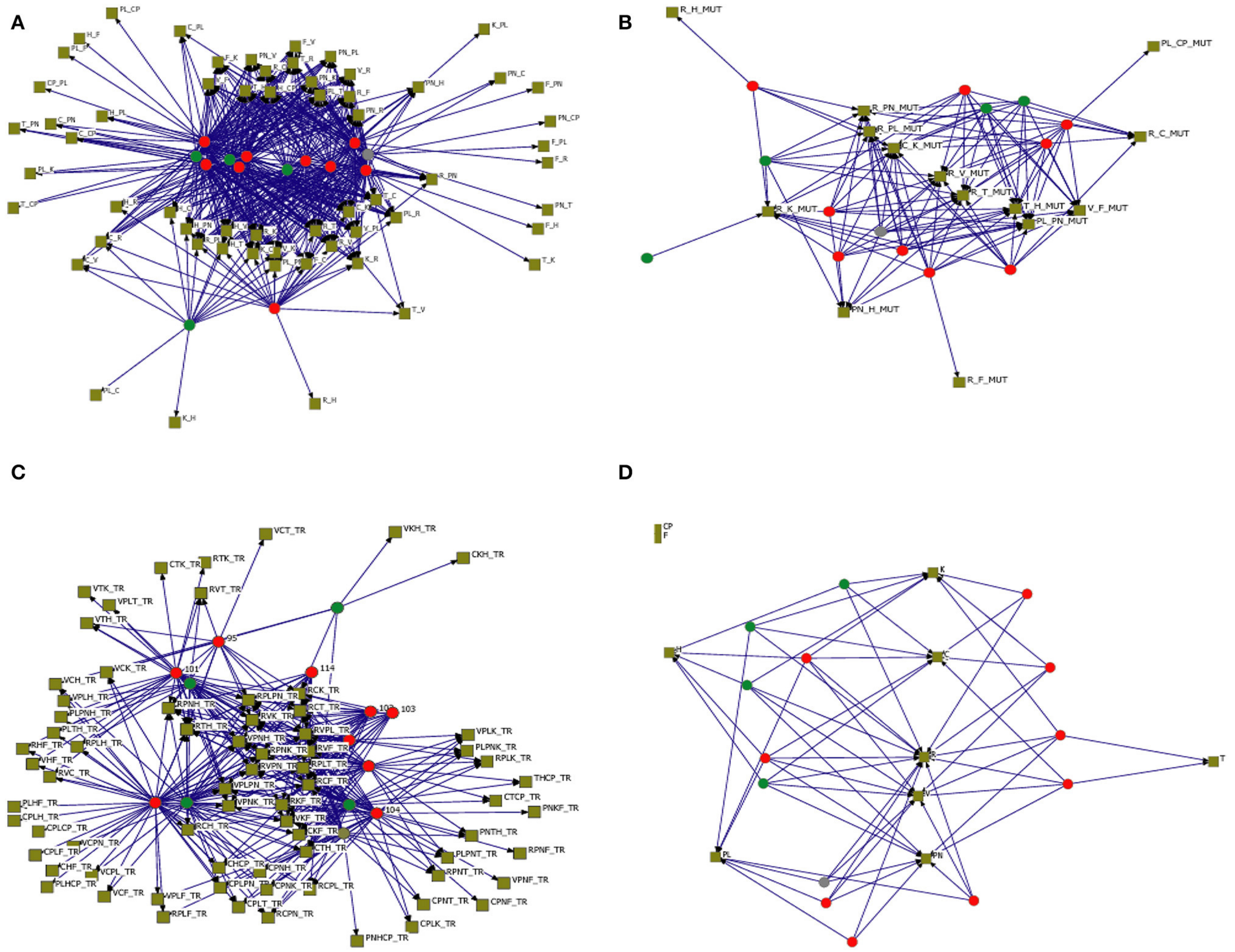


FIGURE 3
Relationship between the occurrence of different types of resource interaction (RI) motifs (boxes) with farm sustainability among the farms of ninth decile (of farm sustainability score). Four types of RI motifs are—**(A)** Tie/linkage; **(B)** Reciprocal ties/linkage; **(C)** Triads; and **(D)** Presence in the Core. The closeness of boxes and circles in the graph-theoretic layout denotes higher tie strength between farms and RI. Color scheme of nodes: FT 1—Red; FT 2—Green; FT 5—Gray. No farms from FT-4 and FT-5 featured in the figures. Nodes are moved minimally to make the labels legible.

Indian Sundarbans. The region is marked by serious biophysical stresses such as salt-water intrusion, prolonged inundation, and seasonal salinity, coupled with extreme climatic events. Moreover, the farm size is extremely small (mostly below one ha) and optimal resource use is key to livelihood sustenance and resilience against vulnerabilities. Resource integration is a survival strategy for the farmers and there are popular instances of resource integration models in the region (Basu et al., 2008; Mandal et al., 2019). While the focus on such models is overwhelming at the policy level, there could be more parsimonious and context-specific interventions in these farming systems. The structural bases (RI motifs) of such resource interactions are scattered across millions of farms in coastal India and they are not necessarily assorted in models, which are demonstrated by research institutions. We tried to decipher the discrete RI motifs that evolved over the years and hold key to the farm sustainability in these fragile socioecological systems.

It is often debated that farm sustainability depends on farm size, although there exist diverse alternative arguments and perspectives (Woodhouse, 2010; Dasgupta et al., 2021), and for our data set, no such association was found between the two. Moreover, an increase in the size of individually-owned farmland is unlikely to occur in most developing nations (Hazell and Rahman, 2014), and it is pragmatic to find ways of achieving sustainability in these smaller parcels of land by using endogenous resources innovatively and efficiently. Parallel to this, evidence suggests a limit to agricultural intensification in densely-populated areas (Jayne et al., 2014; Peng et al., 2022). We try to understand what could happen to farm sustainability had we not intervened externally and let them operate with their existing resources, practices, and technologies. We wanted to know what resource interactions were working well out there and for whom? We argue that farm types in the study regions have distinct characteristics, which have evolved over time, and farm resources and their interactions are among the underlying bases and mechanisms of such evolution (Chopin et al.,

TABLE 1 Occurrence and cooccurrence of resource integrations patterns in the highly sustainable farms.

	Linkages	Reciprocal	Triad	Presence at core
Occurrence of resource interaction leading to high sustainability (ninth decile) (Figures 3A–D)	V->F, F->K, PN->V, R>C, T>H, H>CP, F>V, T>R, PN>PL, PN>K, PL>T, V>R, R>F, PN>R, PN>H, R>PN, T>C, PL>R, C>K, V>PL, R>T, R>V, K>R, F>C, V>K, PL>PN, R>K, K>C, H>V, H>T, H>PN, R>PL, H>C, C>R	R<->PN, R<->PL, C<->K, R<->V, R<->T, T<->H, PL<->PN, V<->F, R<->K, R<->C, PN<->H	ΔR-PN-H, ΔR-T-H, ΔR-PL-PN, ΔR-V-K, ΔV-PN-H, ΔR-PN-K, ΔR-V-PN, ΔV-PL-PN, ΔV-PN-K, ΔR-C-K, ΔR-C-T, ΔR-V-PL, ΔR-V-F, ΔR-PL-T, ΔR-C-F, ΔR-K-F, ΔV-K-F, ΔC-K-F, ΔC-T-H, ΔCH-C-P, ΔC-PN-H, ΔC-PL-PN, ΔC-PN-K, ΔR-C-PL, ΔC-PL-T, ΔR-C-PN	R, V, C, K, PN, PL
Cooccurrence of farm resource interaction pattern interaction leading to higher sustainability (ninth decile) (Figures 4A–D)	K->R, K->C, PL->R, H->CP, H->C, R->PN, F->C, H->T, H->PN, PN->R, R->C, T->R, PN->K, F->K, F->V, H->R, R->V, H->V, R->T, V->PL, PL->PN, V->R, R->F, T->H, PL->T, PN->V, V->F, R->K, V->K, R->PL, C->K, T->C, PN->PL, C->R	R<->K, PL<->PN, R<->T, C<->K, R<->V, T<->H, R<->PL, R<->PN, PN<->H, V<->F, R<->C	ΔR-H-V, ΔR-T-H, ΔR-PN-H, ΔV-PL-PN, ΔV-PN-H, ΔR-PL-T, ΔR-PN-K, ΔR-PL-PN, ΔR-V-PL, ΔR-V-K, ΔR-C-K, ΔR-C-T, ΔR-K-F, ΔV-PN-K, ΔR-V-PN, ΔR-V-F, ΔR-C-F, ΔV-K-F, ΔC-K-F, ΔC-T-H, ΔR-C-PN, ΔC-PN-K, ΔC-PN-H	R, V, PN
Resource interactions that occurred and cooccurred in the farms of the highest decile	V->F, F->K, PN->V, R->C, T->H, H->CP, F->V, T->R, PN->PL, PN->K, PL->T, V->, R->F, PN->R, R->PN, T->C, PL->R, C->K, V->PL, R->T, R->V, F->C, V->K, PL->PN, R->K, K>C, H>V, H>T, H->PN, R->PL, H->C, C->R	R<->PL, R<->V, C<->K, R<->T, T<->H, R<->C, PL<->PN, PN<->H, R<->K, R<->PN, V<->F	ΔR-PN-H, ΔV-PN-H, ΔV-PL-PN, ΔV-PN-K, ΔR-PN-K, ΔR-T-H, ΔR-C-K, ΔR-PL-T, ΔR-K-F, ΔC-K-F, ΔC-PN-K, ΔR-C-PN, ΔR-PL-PN, ΔR-V-PN, ΔR-C-K, ΔR-V-PL, ΔR-V-K, ΔR-C-F, ΔR-V-F, ΔR-C-T, ΔV-K-F, ΔC-T-H	R, V, PN

2015; Thomson et al., 2019). We tell a part of the story of farm sustainability in this article since farms do not sustain by resource interaction only. There is a limit beyond which resource interaction may not work and need external intervention to move to a different sustainability regime (Tittonell, 2014a). We show what "rules of the game" (pattern of RI motifs) operated in small farms, for whom, and how they could have translated into farm sustainability.

Farming systems undergo endogenous intensification due to land constraints (Boserup, 1965), often resulting in the present context of sustainable intensification. Most farms in FT-1 have not felt the pressure of unsustainability, probably due to the larger land size owned by joint extended families and substantial off-farm income that could support the family across seasons. On the other extreme, FT-4 had little resources and access to formal institutions to get themselves extricated from unsustainability and a poverty trap. While FT-2 intensified their smaller lands and earned off-farm incomes to sustain their farm and livelihoods, FT-3 resorted to migration and received off-farm income in the form of remittance. FT-5 diversified and commercialized farming with little dependence on off-farm income. Hence, the Boserupean explanation of agricultural intensification as a response to increased pressure on resources holds partially true for FT-2 and FT-5.

On the other hand, FT-3 demonstrates something close to a Malthusian explanation where farming is abandoned partially for earning off-farm incomes. Interestingly, apart from FT-5, all other FTs depended on off-farm income to sustain their farms and livelihoods. This trend of simultaneous intensification and resource integration in farms and migration is reported in the context of Africa and Asia (Demont et al., 2007; Hua et al., 2019). Similarly, the overarching importance of off-farm income (Supplementary Figure S4) suggests a need to examine further the role of off-farm income in shaping resource-use patterns and farm sustainability. Although there are dissimilarities between different farm types in terms of their characteristics (assets, practices, and outcomes) and abundance of RI motifs (Figure 2), we find only a few unique co-occurrences of RI motifs on the same farm. This suggests that a group of farms can potentially be put on a different sustainability regime (that is, a farm type) just by introducing a minimal number of, or combinations of, RI motifs in farming systems.

We find that particular occurrences (Figures 3A–D) and co-occurrence (Figures 4A–D) of RIs are associated with highly-sustainable farms. This commonality of occurrence and co-occurrence of RI motifs on sustainable farms gives us reasonable confidence to conclude that these motifs are associated with higher farm sustainability. Our analyses have identified 32 discrete linkages, 11 reciprocal linkages, 21 triads, and three core components associated with higher sustainability of small-scale farms since they were associated with highly-sustainable farms and at the same time co-occurred on the same farm. This conclusion is of crucial significance since we not only claim a relationship between RI and farm sustainability but find discrete RI motifs associated with farm sustainability. This is a direct entry point into the design of sustainable farming systems that avoids promoting farming system models that are either too burdensome to accept as such or need significant logistic support and social mobilization to succeed in the long run.

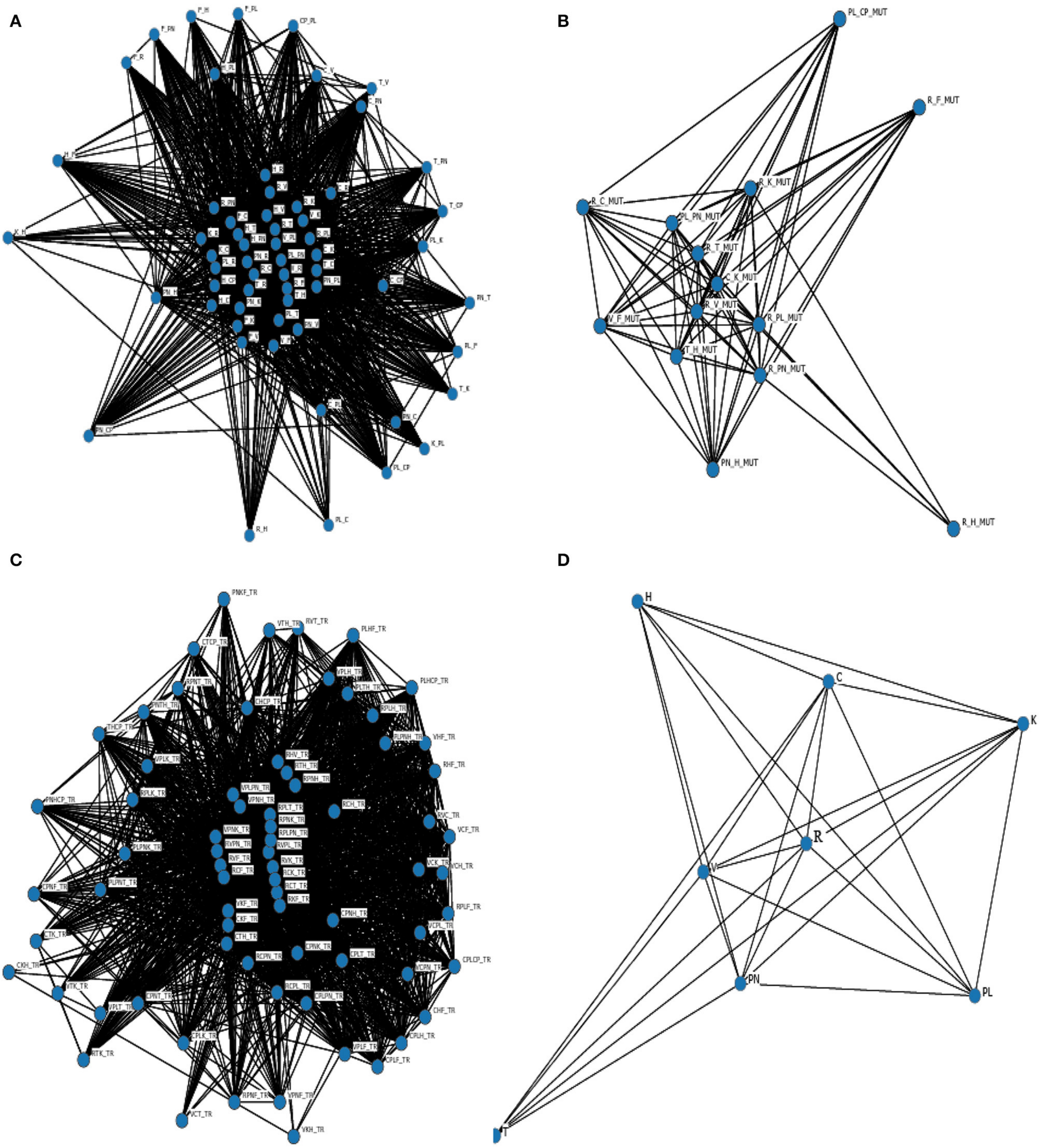


FIGURE 4
Co-occurrence pattern of different types of resource interactions (RI) motifs for the farms of the ninth decile of sustainability score. Co-occurrence patterns for the RI motifs are—**(A)** Tie/linkage; **(B)** Reciprocal ties/linkage; **(C)** Triads; and **(D)** Presence in the Core. The proximity of RIs indicates the similarity of tie strength in a metric multi-dimensional layout of valued data. Nodes are moved minimally to make the labels legible.

Our study results suggest the importance of understanding the network phenomenon of resource interaction in small farms to achieve farm sustainability through informed technological intervention. We could also understand how different farm types engaged different RIs to achieve sustainability, indicating a typology-based intervention strategy. The analysis also reveals the importance of rice-based integrations in farm sustainability of the study areas, followed by vegetables and pond-based integrations with typology-specific variations. Such findings seem realistic because of the large number of waterbodies in the study region and traditional rice-growing lowlands across the region.

TABLE 2 Examples of critically important resource interactions in the study locations.

Resource interactions	Examples
V->F, F->K, PN->V, R->C, T->H, H->CP, F->V, T->R, PN->PL, PN->K, PL->T, V->PL, R->F, PN->R, R->PN, T->C, PL->R, C->K, PL->V, R->T, R->V, F->C, V->K, PL->PN, R->K, K>C, H>V, H>T, H->PN, R->PL, H->C, C->R	Vegetables grown on fallow land; leafy vegetables and wild root crops collected from fallow land; vegetables grown on pond embankment; straw used as cattle feed; trees planted on homestead; homestead wastes dumped/recycled on common property land; extracts of tree leaves used as biopesticide; cantilever poultry cage on the pond; pond water used for kitchen work; poultry housing made out of tree; vegetable waste fed to poultry; harvested rice dried on fallow land; pond water used for critical irrigation of rice; rice by-products used to feed fish; tree leaves fed to livestock; poultry litter used as nutrients for rice; cow-dung used as fuel cake or as a source of biogas; poultry litter used as nutrient for vegetables; rice field boundaries used for plantation; rice field embankment used to grow vegetables; cattle grazing on fallow land; vegetables used in kitchen; poultry litter is fed upon by fish; rice used in kitchen; kitchen waste fed to cattle; vegetables grown on homestead; tree provides shade and biomass to homestead; pond excavated on the homestead land; rice grain fed to poultry birds; homestead used as cattle-shed; cow-dung used as a source of organic manure for rice
R<->PL, R<->V, C<->K, R<->T, T<->H, R<->C, PL<->PN, PN<->H, R<->K, R<->PN, V<->F	Rice-grain fed to poultry and poultry litter used in the rice field; rice field embankment used to grow vegetables, and nutrient residue of vegetables are used by rice; cow-dung used as fuel and kitchen waste is fed to cattle; rice field boundary used for tree plantation, and tree leaves are used as biopesticides; tree grow on homestead land, and the tree provides shade and biomass to homestead land; rice straw fed to cattle and cow dung used as organic manure to rice field; cantilever poultry cage over the pond and fishes feed on poultry litter; pond excavated on homestead land and pond water used to irrigate crops grown on the homestead; rice is cooked in kitchen/straw and stubbles used as fuel, and kitchen waste is converted into manure; pond water is used for the critical irrigation to rice, and rice by-products are used as fish feed; vegetables grown on fallow land
ΔR-PN-H, ΔV-PN-H, ΔV-PL-PN, ΔV-PN-K, ΔR-PN-K, ΔR-T-H, ΔR-C-K, ΔR-PL-T, ΔR-K-F, ΔC-K-F, ΔC-PN-K, ΔR-C-PN, ΔR-PL-PN, ΔR-V-PN, ΔR-V-PL, ΔR-V-K, ΔR-C-F, ΔR-V-F, ΔR-C-T, ΔV-K-F, ΔC-T-H	Rice irrigated by pond water, pond water used for homestead crops, and homestead used for rice nursery bed; vegetables grown on pond embankment, pond water used to irrigate homestead crops including vegetables; pond shares aerial space to poultry cage, poultry litter fed upon by fish, pond water used for irrigating vegetables; pond water used to irrigate vegetables and used for kitchen related works, and kitchen waste goes to vegetables field; rice is irrigated by pond water, pond water used in kitchen, and kitchen waste is recycled and used as manure; tree leaves used as biopesticide, trees are planted on homestead and on the boundary of rice field; rice is cooked in kitchen, straw is fed to cattle, cow dung/straw and stubbles are used as fuel; tree leaves used to produce biopesticides, tree species grown on the homestead land, and rice nursery bed is prepared on homestead land; rice straw/stubbles are used as fuel, rice straw is fed to cattle; rice by-products are fed to poultry birds, tree is used to build poultry house; rice is grown on fallow land, root vegetables on fallow land is cooked in kitchen, fuels of fallow land is used for cooking food; cow dung used as fuel, cattle graze on fallow land; cattle drinks/are cleaned with pond water, pond water used in kitchen, kitchen waste are fed to cattle; rice is irrigated by pond water, straw is fed to cattle, cow-dung is used as crop nutrient; rice is irrigated by pond water, poultry cage is constructed over pond, rice by-products are fed to poultry bird; rice and vegetables are irrigated by pond water, vegetables grown on pond embankment; rice by-product is fed to poultry birds, poultry litter is used as nutrient sources for rice; rice straw and stubbles are used as fuels, rice and vegetables are cooked in the kitchen; cattle grazed on fallow land, rice straw fed to cattle, rice grown on fallow land; vegetables and rice grown on fallow land, rice benefits from the residual nutrient pf vegetables field; rice straw fed to cattle, cattle are fed with tree leaves, tree used to build cattle shed; vegetables grown on fallow land, vegetables cooked in kitchen, biomass of fallow land used as fuels; cattle shed built and tree planted on homestead, tree leaves are fed to cattle
R, V, PN	Rice-based systems connected to livestock, pond, and trees; vegetables-based systems connected to the pond, kitchen and cattle; pond-based systems linked to rice, homestead, poultry, vegetables

In addition to finding that discrete resource interactions are associated with farm sustainability, we also found that the network properties of RIs can explain farm sustainability (Figures 5A, B) without having to include any socioeconomic and biophysical variables in the model. This observation suggests the existence of a network phenomenon of RI on small-scale farms that link to farm sustainability. The linear relationship between "connectedness" (PC1) in RIs and farm sustainability also suggests that higher resource integration can lead to higher farm sustainability. On the other hand, a non-linear relationship between "transitivity and reciprocity" (PC2) and farm sustainability—where sustainability first increases and then declines—suggests a limit to which sustainability could be increased by enhancing reciprocal resource integration or extending the resource integration indefinitely. Considering the types of farms, it emerges that more sustainable farms (mostly FT-1 and FT-2) and less sustainable farms (FT-3 and FT-4) stack at a point of the x-axis as if a sieve is stopping the farms from moving further ahead (Figures 6A, B). This suggests the limit of "connectedness" (or singular integration) and "transitivity and reciprocity" (or reciprocal and extended integration) with available farm resources.

Both sustainable and less-sustainable farms enhance sustainability by increasing RIs, but the less-sustainable farms may not increase the extent of RI due to resource constraints (Figure 6A) and increase reciprocal and extended integration to enhance sustainability (Figure 6B). Already sustainable farms, most likely, do not move ahead with enhanced reciprocation and extension of RIs, perhaps because they achieve sustainability well before the saturation in the integration using all possible resources. Alternatively, there are likely some costs to resource integration, perhaps in terms of labor and/or management complexity, that lead farms to stop once they attain a certain sustainability threshold. Less-sustainable farms continue to enhance reciprocal and extended linkages (instead of one-way linkages) but cannot enhance sustainability beyond a point. Literature also suggests a limit to which such intensification takes place in densely populated areas (Willy et al., 2019; Jain et al., 2020). This is very important to one of our fundamental rationales of the study—to optimize existing resources to achieve farm sustainability. We understand that RI can contribute to higher sustainability for resource-rich farms (with more lands/trees/livestock) and put them on a higher regime of farm sustainability; however, the smaller farms will need external support and innovation to get

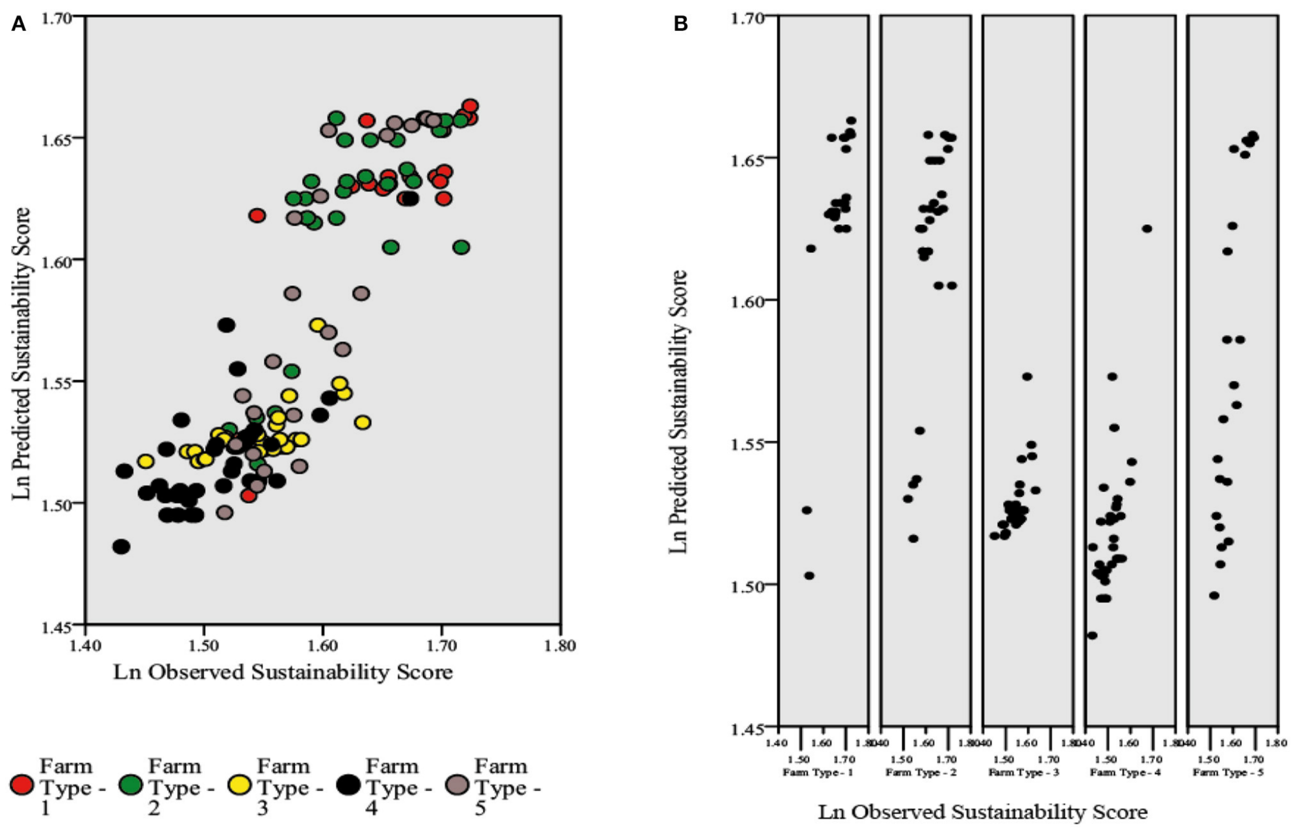


FIGURE 5
Relationship between the observed and predicted value of sustainability score **(A)** for all farms taken together and **(B)** for five farm types separately. Predictor variables are two principal components extracted from 11 network properties of farm resource interaction. The output is based on the three best-performing models in terms of their correlation value and relative error.

out of the unsustainability trap (Supplementary Figure S4). Also, sustainable farms have demonstrated a limit to sustainability which can be extended by introducing innovations and policy regulations that operate outside the scope of the farm resource use (such as marketing support, and tax reforms). Further, despite the limit to achieving sustainability with enhanced resource integration, there remains considerable variation in the magnitude of sustainability within the same farm type, suggesting farm-specific refinements within the broader scope of typology-specific interventions. On the other hand, the alternative agricultural movements, despite their huge potential, ask for investment in social capital and institution building (Rosset et al., 2011; Dorin, 2022). We argue that our approach is considered a value-added tool to those long-term efforts for transforming agricultural value chains.

5. Conclusion

Farm sustainability is often framed along a dichotomy of external input-driven farming and internally-sustained agroecological farming. While helpful in comparing key differences, this dichotomy ignores the critical observation that smallholder farms are typically distributed between these two extremes and can change their nature over time. Moreover, wholesale adoption of more integrated and "agroecologically" informed farming models is often dependent on region-specific details and exceptional social learning for mass popularization. The present study demonstrates a very different approach, more endogenous to farms themselves, by linking farm sustainability with the network properties of a farm's resource-use patterns. It also identifies discrete resource-interaction strategies that help farmers to achieve long-term sustainability. This work points to a more incremental path toward sustainability, in contrast to a wholesale transformation, which can be challenging for smallholder farms that may be risk-averse due to their already marginal socioeconomic status. Thus, the results support the argument that the promotion of discrete resource interactions can move farms along the sustainability gradient more parsimoniously (Goswami et al., 2016).

We acknowledge that sustainability in small-scale farms cannot be improved indefinitely by creating new RIs on the farms, and there is a limit to such achievement for different farm types. We understand that feasible actions on a farm are often guided by a set of biophysical and socio-political realities that fundamentally guide and constrain on-farm decision-making. Ultimately, farmers' capacity to achieve critical RIs must be understood within the broader framework of culture, power, and access to resources. Our analysis does not intend to side-step those broader issues, which fundamentally affect the success of agricultural development efforts

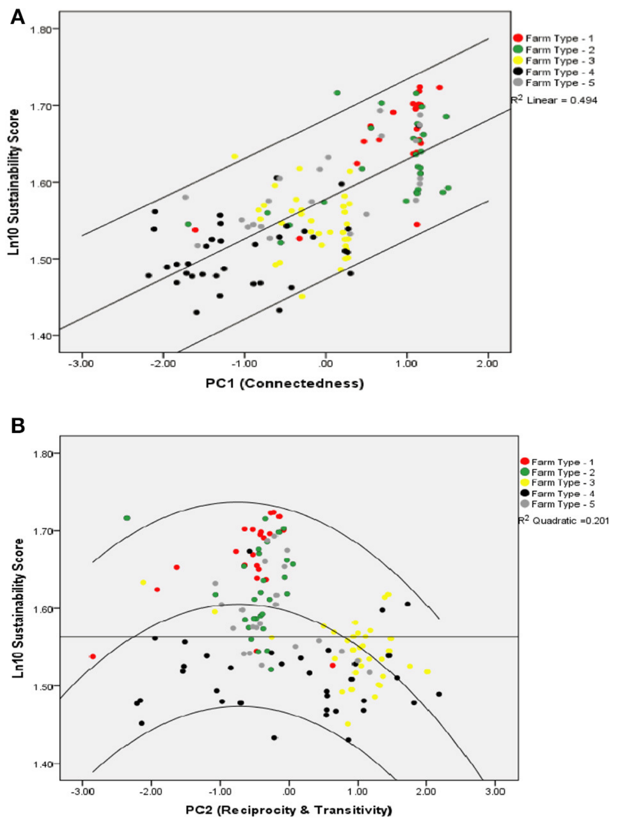


FIGURE 6
Relationship between the principal components (PC) of network properties of resource interaction and farm sustainability for different farm types. Two PCs, namely PC1 (Connectedness) and PC2 (Reciprocity and Transitivity) are extracted from 11 network properties, and the sustainability score is measured by a composite index. **(A)** PC1 shows a linear, and **(B)** PC2 shows a non-linear relationship with farm sustainability score. Lines flanking the trendline are confidence intervals, and the horizontal line is the median sustainability score.

worldwide, enriching our understanding of the crucial elements of farm sustainability.

This novel approach opens up the possibility to theorize farm sustainability as an outcome of the network phenomenon of resource utilization. It explains the structural bases of sustainability (the RI motifs) that could help design farming systems to achieve a set of desired outcomes. This is analogical to deciphering the "genetic code" of farming systems that holds the key to their sustainability, and this can open up a fundamentally different way to study farm sustainability.

In this study, the identified RI motifs (32 linkages, 11 reciprocal linkages, 21 triads, and three resources at the core) should receive attention from agricultural research to develop appropriate technology and extension for the participatory design of the farming system to achieve different pathways to farm sustainability in coastal India. For example, in the study areas, pond-based interventions hold key to the farm sustainability when a farm owns (and is ready to spare) enough land to dig/expand the pond area. Moreover, such action might involve substantial investment, which could be channelized through public-funded land development schemes. The smaller motifs (e.g., triads) of resource interaction can act as potential entry points for on-farm experimentation involving existing or new agro-technologies. For smaller landowners, resource recycling plans may be developed in a participatory manner and supported by external inputs and collectivization mechanisms. A large proportion of farm income is earned through non-farm income but rarely invested back in farming. It is important that circular investment be ensured by external or remittance-supported means to sustain productive farming. This may be in the form of small livestock or excavation of water harvesting structures, thus extending the limit of small farms' ability to enhance sustainability through resource recycling. The analytical approach may also be extended to study differential structures of RI networks in different agroecological regions and open up a new stream of functional research in farming systems research and development.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Ethical Committee at the IRDM Faculty Centre, RKMVERI. 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.

Author contributions

RG and SN conceptualized and designed the study. SP, PD, and RG collected and supervised field data collection. RG analyzed data in discussion with SN. RG, SN, SB, and BM participated in writing, editing, and commenting on 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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Supplementary material

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EDITED BY
Francis Kumi,
University of Cape Coast, Ghana

REVIEWED BY
Shadrack Kwadwo Amponsah,
CSIR Crops Research Istitute, Ghana
Emmanuel Wisgtos Inkoom,
University of Cape Coast, Ghana
Mohd. Muzamil,
Sher-e-Kashmir University of Agricultural Sciences and Technology, India
Adewale Sedara,
Iowa State University, United States

*CORRESPONDENCE
Bekele Hundie Kotu
b.kotu@cgiar.org

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Enhancing smallholder maize shelling mechanization through the collective business model: the case of Northern Ghana

Isaac Gershon K. Ansah[1], Bekele Hundie Kotu[2]*, Benedict Ebito Boyubie[3] and Joseph Ekow Bonney[4]

[1]Department of Economics, University for Development Studies, Tamale, Ghana, [2]International Institute of Tropical Agriculture, Accra, Ghana, [3]International Institute of Tropical Agriculture, Tamale, Ghana, [4]Department of Agricultural and Food Economics, University for Development Studies, Tamale, Ghana

This paper assessed the conditions contributing to the success of smallholder farmer groups in northern Ghana using mechanical maize shellers (MMS) based on a collective business model. A sample of 156 farmers from 18 intervention communities was analyzed using qualitative comparative analysis (QCA) to examine the conditions necessary to increase usage of MMS. The results revealed a single configuration for achieving high group MMS usage, observed in about 24 percent of the cases. This configuration comprises five sufficient conditions: high cooperation, good relationships among members, payment of financial contributions, provision of prior notice for group meetings, and obedience to group rules. Additionally, two necessary conditions identified were low conflict and reduced use of manual maize shelling. When these core conditions coexist within the farmer groups, the MMS is more likely to be highly utilized. These findings suggest that group leaders and members should encourage mutual understanding, respect individual differences, value diverse opinions, and share responsibilities to improve cooperation, foster better relationships, and reduce conflicts among members. This approach can encourage both existing and new members to utilize the services of mechanical sheller groups, ensuring sustainability. Future research should utilize alternative econometric procedures to evaluate the configurations identified by the QCA analysis, aiming to enhance the reliability and confidence of empirical findings.

KEYWORDS

maize-sheller, qualitative comparative analysis, group business model, collective action, Ghana

1 Introduction

Agricultural mechanization is a necessary condition for agricultural intensification and modernization since it improves production capacity and land output rates (Devkota et al., 2020; Peng et al., 2022). Mechanization transforms the traditional labor-based agriculture to modern technology-based agriculture and improves input-use efficiency (Kusz, 2014; Devkota et al., 2020). Fischer et al. (2021) and Zhang et al. (2017) reported that mechanization creates a division of labor, enhances specialization and reduces drudgery. Others have argued that mechanization also stimulates smallholder farmers to scale up their production activities for commercialization and competition (Pingali, 2007; Li et al., 2021; Liao et al., 2022).

Maize is one of the dominant crops in Ghana in terms of area cultivated and volume of production (MoFA, 2022) which has attracted the attention of researchers, development practitioners, and policy makers with regards to mechanization (Houssou et al., 2013; Diao et al., 2014; Darfour and Rosentrater, 2016). Mostly contributed by smallholder farmers, Ghana's annual maize production has reached over 3 million metric tons since 2019 (MoFA, 2022) which has been difficult to achieve without mechanization. However, the maize value chain is mostly mechanized in pre-harvest activities such as land preparation while postharvest activities have been given marginal attention (Houssou et al., 2013; Diao et al., 2014; Darfour and Rosentrater, 2016). While maize shelling is the most power-intensive postharvest activity which entails mechanization, it is often done manually (using hand and sticks; Darfour and Rosentrater, 2016). The most challenging aspect of manual maize shelling is that it is laborious and time-consuming while labor is getting scarcer among smallholder farmers in SSA (Pingali, 2007; Baudron et al., 2019; Fischer et al., 2021). Moreover, manual shelling reduces grain quantity and quality (Gebeyehu, 2023), causes burning sensation in the palm and fingers as well as impaired functioning of some arm muscles and joints and may affect the body posture due to continuous sitting, thereby leading to a poor musculoskeletal health (Joshi et al., 2018).

Despite these limitations of the manual maize shelling method and the potential of mechanization to address those issues, smallholder farmers have limited access to mechanization services (Fischer et al., 2021; Gebeyehu, 2023; Kotu et al., 2023). While mobile commercial service providers for maize shelling operate in limited locations of farming communities in northern Ghana, mostly they target large and medium scale maize farmers due to better economies of scale. Moreover, smallholder farmers are not attractive customers for commercial shelling service providers because of their small quantities of produce and financial constraints to pay for rental services.

Collective action is one way to overcome the limited resource constraint confronting smallholders and the diseconomies of scale associated with small volumes of production among smallholders (Poteete and Ostrom, 2004; Fraser et al., 2019). Collective action helps farmers to pull their resources, talents, skills, knowledge and power to fulfill goals that cannot be achieved individually (Poteete and Ostrom, 2004; Fraser et al., 2018; Ureña et al., 2019). Collective action also increases recognition and feelings of self-worth and reduces exclusion (Dong et al., 2018). Nevertheless, some collective actions may also lead to negative sociocultural consequences, such as humiliation and conflict, especially in groups with poor group dynamics or cohesiveness (Ureña et al., 2019; Van de Brake et al., 2020). For instance, the unequal ability of group members to contribute to collective tasks, free-riding and appointment of ineffective leaders may reduce cohesiveness and lead to potential conflict (Gençer, 2019; Bakir et al., 2020).

The success, vis-a-vis the sustainability, of collective action groups depend on the set of principles or institutions guiding the interaction of participants and associated factors including member characteristics and institutional support (Bowles and Gintis, 2002; Rodrik et al., 2004; Skoog, 2005; Bartolini and Santolini, 2017). Ombogoh et al. (2018) observed among smallholder farmers in Kenya and Uganda that farmer groups that practiced the 'inclusive decision making' principle were less likely to collapse. This model of decision making includes all members' views and opinions in decision making, which in turn increases their self-worth. Ochieng et al. (2018) found in Central Africa that farmers' groups that adopted the 'participatory market research' principle had high market performance due to their abilities to penetrate high-value markets. In Japan, working in small groups and having frequent meetings were the two leading factors that enhanced the success of collectively managed irrigation systems (Takayama et al., 2018). While most of the group principles are often organized locally by group leaders and their members, sometimes other rules are devised at the higher level by government agencies. An example is Ghana's 'Plants and Fertilizer Act', which presented farmer groups and individual farmers, especially maize farmers, an unlimited choice of improved seed varieties (Poku et al., 2018).

Despite acknowledging the importance and potential benefits of collective action in overcoming resource constraints and achieving better economies of scale, there is a scarcity of empirical evidence and comprehensive studies focusing on the conditions essential for the success of these collective initiatives, particularly in the domain of agricultural mechanization within smallholder farming communities. The existing literature provides insights into the advantages of mechanization in transforming agriculture and highlights the challenges faced by smallholder farmers in accessing mechanization services (Houssou et al., 2013; Diao et al., 2014; Fischer et al., 2021; Hodjo et al., 2021; Peng et al., 2022; Kotu et al., 2023). However, the specific factors that contribute to the success or failure of collective efforts in adopting mechanized maize shellers among these farmers remain underexplored. This gap in research hampers the comprehensive understanding needed to design effective interventions and support mechanisms for enhancing agricultural mechanization within smallholder farming contexts, limiting the development of sustainable collective business models in this domain.

The objective of this study was to examine the collective action efforts of smallholder farmers with regard to mechanical maize shellers and the conditions that contribute to their successes. Based on the theory of collective action and the qualitative comparative analysis (QCA), the study identified the possible contextual factors that can enhance the success of the group business model adopted by smallholder farmers in northern Ghana. The cases considered are farmers' groups which were organized and supported by the Africa RISING project[1] around mechanical maize shellers (MMS) (see details of MMS groups in Section 3.1). The MMS were organized based on the assumption that, in the presence of financial scarcity among smallholder farmers in northern Ghana and the low scale production by these farmers, the group business model would be attractive to more farmers than the individual business model. This assumption is supported by studies elsewhere in Africa (Fischer et al., 2021; Kotu et al., 2023). For instance, Kotu et al. (2023) found that about 65% of smallholder farmers in their sample were willing to invest in mechanized maize shelling within the group business model while only about 10% of them would like to do so within the individual business model.

1 Africa RISING is a research-for-development project which was sponsored by the United States Agency for International Development with the aim of reducing poverty among smallholder farmers through innovating and scaling of sustainable agricultural practices and technologies. It was operational in six countries (i.e., Ghana, Mali, Tanzania, Malawi, Ethiopia, and Zambia) from 2012 to 2022 involving several international and national research institutions, development NGOs, and the private sector (visit https://africa-rising.net/ for more info).

The study contributes to the limited evidence around business models in smallholder agriculture in general and agricultural mechanization in particular. From a managerial perspective, this research contributes to stakeholders recognizing the aspects necessary and sufficient to achieving better group goals in a collective action, given the empirical results from the MMS groups. Furthermore, our study adds to the few but growing applications of the QCA in empirical studies in Agriculture (Florea et al., 2019; Ndimbo et al., 2023) which is useful to make scientifically valid comparisons of cases in the context of small sample size (Ragin, 2000; Rihoux and Ragin, 2009; Blackman, 2013).

2 Theoretical framework

This study adopts Olson (1965) theory of collective action to explain the conditions under which a smallholder maize farmer would participate in a mechanical maize sheller (MMS) group, with the willingness to shell a greater percentage, if not all, of the harvested produce using the group's mechanized sheller instead of any other service, and ensure its sustainability. The hypothesis is that a farmer incurs cost (C) by joining the MMS group. This cost consists of a fixed cost of the sheller (A), variable cost for operating and maintaining the sheller (B) and the rate (r) corresponding to quantity of maize shelled by the farmer. The total cost per person is thus a function of the rate: $C = f(r) = A + Br$.

Further, the study assumes that the only benefit to the farmer is r. Therefore, total group benefit (B_g) depends on the group size (N_g), such that $B_g = N_g r$. The share of benefit for the farmer (P_i) is the ratio of the farmer's benefit (B_i) to the total group benefit $\left(\text{i.e.,} P_i = B_i / B_g\right)$. A rational farmer will consider his/her individual absolute advantage, $A_i = B_i - C$, and if it is positive, the farmer will join the MMS group. A profit-maximizing farmer will compare changes in the individual's absolute advantage (A_i) to changes in the rate (r), as specified in (1) below:

$$dA_i/dr = dB_i/dr - dC/dr = 0 \quad (1)$$

Thus, a profit-maximizing farmer will join the MMS group up to the point where the additional benefit of shelling an extra unit of maize equals the additional cost, as specified in (2) below.

$$dB_i/dr = dC/dr \quad (2)$$

The sustainability of the MMS group depends on the additional collective benefit with respect to the extra unit of maize shelled. Noting that in (2), $B_i = P_i B_g$, the expression becomes as specified in (3) below.

$$dP_i B_g/dr = dC/dr$$

$$P_i\left(dB_g/dr\right) = dC/dr$$

$$dB_g/dr = 1/P_i\left(dC/dr\right) \quad (3)$$

Therefore, the MMS group will be utilized and sustained if the additional collective benefit of the group is equal to $1/P_i$ times the additional cost of joining the group (i.e., at an optimal condition). The group will also be sustainable if the ratio of collective benefit to the cost is greater than the ratio of collective benefit to individual benefit $\left(\text{i.e.,} B_g/C > B_g/B_i\right)$ (increasing condition). More members patronizing the group sheller implies a greater group benefit, including higher revenue to run and maintain the group sheller. For high usage to happen, there should be a set of conditions that foster collective action in the MMS group.

3 Methodology

3.1 Farmers' groups on mechanical maize sheller

In December 2018, the Africa RISING project demonstrated small-scale mechanical maize shellers (MMS) to farmers in 18 communities of Northern, Upper West and Upper East regions of northern Ghana (Kizito et al., 2018). The MMS had a four horsepower (hp) engine capacity which could shell up to 1.5ton of maize per hour.[2] Realizing that farmers were highly motivated during the demonstration events to mechanize maize shelling and that they had severe financial constraints to purchase MMS, the management of the Project decided to donate the shellers to the farmers on condition that they (1) form groups (each group having 15–25 members), (2) jointly mobilize starting operating capital from registered members (Ghs800 = $156 = 25% of the shellers' market value), (3) develop self-written constitutions,[3] (4) operate and maintain the shellers according to the self-written constitutions, (5) ensure a gender balance in leadership (Odhong, 2019). The machines were transferred to 18 farmers' groups (one per community) in October 2019 after checking the fulfillment of these conditions. Following the transfer of the machines, selected group members were trained on basic repair and maintenance. Moreover, the groups were linked to local artisans so that they could get professional supports on maintenance, customization of the machines to their needs, and repair services, if required.[4] As indicated in their written constitutions, most of the

2 The machine comprises three main parts: diesel engine, concave-shaped chamber where the shelling takes place, and a hopper. The shelling chamber houses a shelling drum on which a narrow beating ridge is mounted, a coarse screen, and collecting pan. In operation, the diesel engine powers a shaft that rotates the shelling drum [see Supplementary Figure A1 in the Annex; also refer to Mutungi et al. (2022) for more description, benefits and procedures of using the machine].

3 The farmers were trained on how to develop a written constitution.

4 More information on the trainings can be found on these links: https://cgspace.cgiar.org/handle/10568/16926; https://africa-rising.net/no-technician-no-problem-africa-rising-releases-35-vernacular-diy-videos-on-maintenance-of-maize-shelling-machines-for-use-by-farmers-in-ghana/.

groups agreed to provide two types of services to their members including shelling services at payment and loan services to those who need. In addition, they agreed to provide shelling services to non-member farmers to generate more income.

3.2 Data source

This study used survey data collected in March 2021 by the International Institute of Tropical Agriculture (IITA) in the intervention communities regarding the mechanized maize shelling.[5] The sampling frame consisted of all individual members (about 320) of maize sheller groups organized in 18 communities. To obtain adequate representation from each maize sheller group, 50% of the total members from each group were selected from members' lists using the simple random sampling method, resulting in a sample size of 162 farmers. This sample size was slightly above the statistically required sample size (i.e., 147 farmers) following Cochran (1977).[6] The sample size per farmers' group ranged from 5 to 12 with an average of 9.[7] A semi-structured questionnaire was used to collect the data from the sampled farmers. Interviews with individual members focused on their household resources, maize produce, methods of shelling before and after the introduction of the group sheller, use of group services, knowledge of group rules and participation in decision making process, member interactions (conflicts and cooperation), perception regarding how maize sheller should be managed. After data cleaning, 156 responses were used for the analysis due to missing information from the remaining 6 farmers.

3.3 Empirical strategy: understanding factors influencing MMS usage

The sustainability of the MMS group depended on farmers' usage of the sheller, making it crucial to examine the conditions collectively leading to increased usage, as underutilization of the machine would lead to undesirable cost and revenue implications. These conditions were expected to represent various causal pathways affecting the MMS group, with some being necessary and others being sufficient. We used the Qualitative Comparative Analysis (QCA) methodology to analyze the data. The QCA was selected as it is useful to make scientifically valid comparisons of cases in the context of small sample size like ours (Ragin, 2000; Rihoux and Ragin, 2009; Blackman, 2013). Eight key variables or conditions were considered in the study, which are detailed below.

5 The survey process was reviewed and approved by the Institutional Review Board of the International Institute of Tropical Agriculture.

6 Sample size = $\frac{P(1-P)}{\frac{e^2}{z^2}+\frac{P(1-P)}{N}}$ = 147, assuming 5% marginal error (e), 1.65 z-score (z), 50% population proportion (P), and 320 population size (N) (Cochran, 1977).

7 Although the farmers were advised to organize their groups within the range of 15 to 25 group size, farmers in one of the communities in Upper East region could mobilize only 10 farmers for membership. The group was considered for project support as a special case.

3.3.1 Usage of group sheller (Y)

This is the outcome variable, representing the proportion of maize harvest shelled using the group sheller machine. A higher value indicates greater utilization, typically if the proportion was larger than 0.5. Conversely, a lower value denotes underutilization.

3.3.2 Cooperation (D)

This variable signifies the level of cooperation among group members. A value of 1 indicates perceived cooperation among members, while 0 implies the opposite.

3.3.3 Quantity of maize output shelled manually (E)

This variable represents the extent of maize shelled manually. A higher proportion (e.g., > 0.5) implied manual shelling was present; otherwise, it is marked as absent.

3.3.4 Rule obedience (F)

It reflects farmers' perceptions regarding the adherence of group members to constitutional rules. A value of 1 indicates perceived obedience, while 0 implies the opposite.

3.3.5 Group relationship after machine (G)

This variable indicated farmers' perceptions of improved relationships among group members following the introduction of the mechanized sheller. It is marked as 1 if there was perceived improvement and 0 otherwise.

3.3.6 Info received prior to group decision-making (H)

It represents whether members were informed before group decision-making processes. A value of 1 denotes pre-information, while 0 signifies otherwise.

3.3.7 Contribution to group decision-making (I)

This variable assesses the active participation of members in group decision-making. If a member contributed, it is marked as 1; otherwise, it is 0.

3.3.8 Group contribution (J)

It signifies whether a farmer fulfilled financial obligations within the group. A value of 1 denotes meeting these obligations, while 0 signifies not doing so.

3.3.9 Conflict in group (L)

This variable indicates whether farmers observed conflicts among group members. A value of 1 represents observed conflict, while 0 indicates its absence.

These variables/conditions can be grouped into two sets, namely: the crisp set and the fuzzy set. The crisp set represented binary variables, indicating either membership (1) or non-membership (0). These variables distinctly fit into clear-cut categories without any intermediate degrees. For example, whether a member actively contributed to group decision-making (1 if yes, 0 if not) is a crisp set. The fuzzy set included variables which do not fit into a clear-cut category, but have varying degrees of membership with values lying between 0 and 1. For instance, the proportion of maize output manually shelled might be represented as a fuzzy set. A value closer to 1 implies a higher proportion shelled manually, while closer to 0 indicates a lower proportion.

Using the QCA, the relationships between the eight conditions (i.e., D, E,..., L) and the outcome (Y) were analyzed. QCA labels the sets conventionally using lower and upper cases. In crisp sets, uppercases represented a value of 1 (i.e., full membership) and lowercases represented a value of 0 (i.e., full non-membership). With fuzzy sets, uppercases showed the degree of set membership (e.g., the value of D) and lowercases showed the degree of set non-membership (e.g., 1 minus the value of D). Accordingly, QCA identified different combinations of variables (e.g., D*E, D*e, d*E, d*e in the case cooperation and quantity of maize output shelled manually) to assess their impact on the outcome (Y). In the crisp-set case, the relationship between the predictors and the outcome were evaluated using conditional probabilities (e.g., Pr(Y|D*E), where higher conditional probabilities implied the statement "D*E was a subset of Y," or, in logical terms, "if D*E, then Y"). In the fuzzy-set case, individuals were considered more or less a member of a particular set (e.g., 0.33 would indicate "more out than in, but still somewhat in" the set, whereas 0.7 would signify "more in than out, but not entirely in" the set). To combine fuzzy sets into configurations, the minimum operator, e.g., D*E = min(D, E), or d*E = min[(1 – D), E] was used.

The analysis evaluated these combinations, considering both crisp and fuzzy sets due to the presence of continuous and binary variables in the dataset, to identify configurations significantly contributing to higher or lower usage levels. The goal was to identify the optimal combination of factors that impact MMS usage. To evaluate this relationship, an inclusion ratio or consistency score was calculated following Ragin (2006) as follows:

$$I_{XY} = \frac{\Sigma min(x_i, y_i)}{\Sigma x_i} \quad (4)$$

where X is the predictor configuration, Y signifies the outcome set, x_i stands for each case's membership in the configuration X, and y_i stands for each case's membership in the set Y. Equation (4) calculates the consistency score by comparing how many cases in configuration X are also part of the outcome set Y. A higher value closer to 1 shows greater consistency, suggesting that X is a subset of Y.

Sufficient configurations were then condensed to a more concise solution, assessed based on coverage, the degree to which the solution explained the outcome. Based on Ragin (2006), coverage (C_{XY}) was computed as specified in (5) below.

$$C_{XY} = \frac{\Sigma min(x_i, y_i)}{\Sigma y_i} \quad (5)$$

This equation computes the coverage, indicating the extent to which the solution (X) explains the outcome (Y). A higher value implies that more of Y is covered or explained by X.

4 Results

4.1 Framers' socio-demographic characteristics and shelling methods used

Table 1 displays descriptive results on some basic variables. About 53 and 47% of male and female farmers were, respectively, sampled for the study. In rural Ghana, men are more involved in agricultural production (GSS, 2021b). However, women are more engaged in post-harvest activities (FAO, 2018). The average female farmer (52.9 years) in the sample is about 6 years older than the average male farmer (46.6 years). About 74% of farmers have no formal education, indicating high illiteracy rate in the study area. According to the GSS (2021a), educational attainment among the aged in rural Ghana is low, as rural areas lack appropriate infrastructure and face other institutional rigidities (Barrett et al., 2019).

Furthermore, the results show the presence of a substantial difference between male and female farmers in terms of formal education, i.e., 37% of male farmers and 14% of female farmers have formal education, which confirms the evidence that females are disadvantaged in terms of access to education (Senadza, 2012). About 61% of farmers are monogamously married. More male sample farmers are in polygamous marriages compared to female farmers,

TABLE 1 Socio-demographics, role and shelling method(s) used by participants.

	Male *n*=83	Female *n*=73	Total *n*=156	Chi²/*t*-value
Age (years)	46.6	52.9	49.5	2.74***
Education (%)				
Educated	31 (37.3)	10 (13.7)	41 (26.3)	17.29**
Not educated	52 (62.7)	63 (86.3)	115 (73.7)	
Marital status (%)				
Single	1 (1.2)	0 (0.0)	1 (0.6)	43.83***
Monogamous	51 (61.5)	44 (60.3)	95 (60.9)	
Polygamous	31 (37.4)	5 (6.8)	36 (23.1)	
Divorced/ Widowed	0 (0.0)	24 (32.9)	24 (15.4)	
Roles (%)				
Ordinary members	52 (62.7)	53 (72.6)	105 (67.3)	32.90***
Leaders	31 (37.3)	20 (27.4)	51 (32.7)	
Manual shelling (%)				
Yes	38 (45.8)	26 (35.6)	64 (41.0)	1.66
No	45 (54.2)	47 (64.4)	92 (59.0)	
Commercial shelling (%)				
Yes	13 (15.7)	0 (0)	13 (8.3)	12.47***
No	70 (84.3)	73 (100.0)	143 (91.7)	
Mechanical shelling (%)				
Yes	53 (63.9)	53 (72.6)	106 (67.9)	1.36
No	30 (36.1)	20 (27.4)	50 (32.1)	

while more female farmers are also divorced or widowed compared to male farmers. The dominance of Islamic religion in northern Ghana allows men to have more than one wife while women find it difficult to remarry even after divorce or after the demise of their husbands. The majority of farmers (67.9%) used the group mechanical shellers provided by Africa RISING. Even though more female farmers use the group sheller machines than their male counterparts, the difference is not statistically significant. About 41% of farmers shell their maize manually, while about 8% of the farmers shelled their maize using commercial shelling services. While about 16% of male farmers use commercial maize shelling services none of the female farmers do so.

4.2 Maize quantity produced and proportion shelled by different shelling methods

Table 2 displays quantity of maize produced in 2020 cropping season and the shelling methods used by farmers. Farmers harvested an average of output about 556 kg. In most rural areas, especially in northern Ghana, men have more physical access to land compared to women, making male farmers more likely to cultivate larger acreages of land and produce higher output than female farmers. This was the case in the study, where the average male maize farmer produced about 223 kg more than the average female maize farmer. In terms of shelling, the average farmer shelled about 25% of the total maize produced manually and 6% using commercial services. Male farmers shell about 12% of their total maize production using commercial services, but no female farmer accessed commercial shelling services. With the MMS group machine, farmers used it to shell about 62% of their total maize output in 2020. Female farmers significantly shelled a higher proportion (69%) of the total maize produce with the MMS compared to male farmers (55%). Women perform more household chores than men in Africa (Chahalis et al., 2021). This means that women are more likely to embrace a technology that helps them to save labor time, as in the case of the mechanical maize sheller. Therefore, it is not surprising that women shelled a greater proportion of their maize using the group machine.

TABLE 2 Quantity of maize produced and proportion shelled by various methods across genders.

	Male *n*=83	Female *n*=73	Total *n*=156	Diff.	*t*-value
Quantity produced (kg/year)	659.8	437.2	555.6	222.6	3.24***
Manually shelled (%)	26.2	23.4	24.9	2.8	0.43
Commercially shelled (%)	11.5	0.0	6.1	11.5	3.44***
Mechanical machine shelled (%)	55.0	69.0	61.6	−14.0	−1.94*

4.3 Factors associated with group sheller usage

The most important elements to ensuring sustainability in collective action are cooperation and good relationship (Bakir et al., 2020). From the results in Figure 1, about 78% of participants affirmed that there is high cooperation within their groups, while about 87% of participants perceived that members have better relationships within their groups. Due to this, there is very low conflict in the groups; only about 6% reported that they were aware of conflicts in their groups. Rural people often exhibit a high level of social solidarity and unity, which makes them work collectively and effectively (Gongbuzeren et al., 2021), leading to better relationship and cooperation. The high level of cooperation and relationship among participants highlight the advantages of well-organized collective action (Dong et al., 2018). With the availability of mechanical shellers, farmers will be less motivated to shell their maize manually. Therefore, most participants shelled larger proportions of their maize with the mechanical group shellers. Responses from some of the participants reveal that a few of them shelled their maize manually due to low output or the sheller was malfunctioned when they wanted to shell.

In terms of group rules, majority of participants (76.3%) stated that members obey the group rules. In addition, about 80% of participants fulfill their financial obligations. According to Reina et al. (2021), decision-making is complex and may lead to conflict; however, effective decision ensures the success of a collective action. In the sample, about 72% of the participants revealed that they are usually pre-informed before group decisions are made, while about 42% contribute actively to group decision-making.

4.4 Conditions for increasing group sheller usage and enhancing sustainability

4.4.1 Possible configurations and best-fit solution

The key initial step in QCA is to ascertain the configuration that contains the highest number of individuals through best-fit solutions. The best fit solution is used to assess the combination of causal conditions and how they are distributed across the cases (farmers). With eight causal conditions, there are 2^k ($2^8 = 256$) logically possible configurations. Figure 2 reports 35 of these 256 combinations of conditions that have at least one case (farmer) with greater than 0.50 membership.

The results show that only 1 farmer (0.64%) is likely to experience all of the independent measures at above-mean levels (DEFGHIJL). The most common configuration is DeFGHiJl, with approximately 18% of the sample best fitting it. This configuration corresponds to high group cooperation, less manual shelling of produce, high rules obedience, better within-group relationships, frequent or consistent prior notice to meetings, low participation in group decision-making, high commitment to group contributions and low levels of conflict within the group.

4.4.2 Overlap between conditions and mechanized maize sheller usage

Next, the relationship between the various conditions and group sheller usage were examined through the coincidence matrix, which

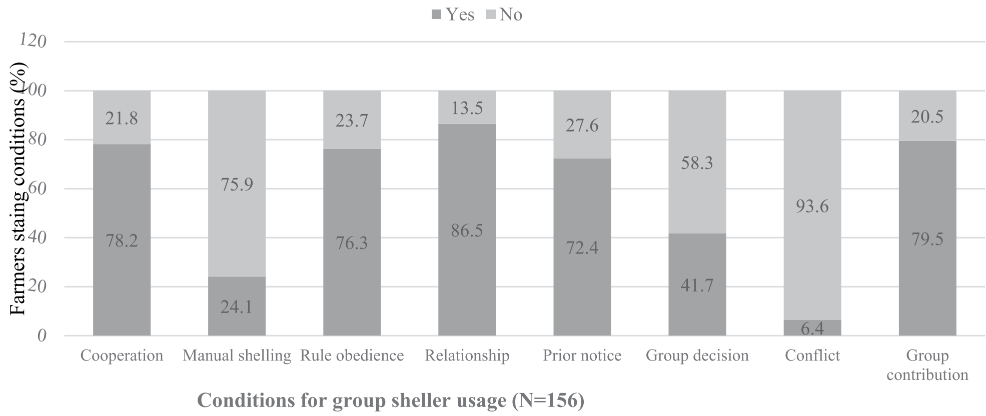

FIGURE 1
Distribution of conditions used in assessing group sheller usage.

helps to understand the relationship between the conditions by measuring the amount of overlap or coincidence between the two sets or configurations. The outcomes are reported in Table 3. The results show that the high cooperation and high MMS usage set overlap by 59% of their possible shared area, as shown by their 0.592 coincidence score.

High conflict and high MMS usage sets overlap the least, by only about 1.3% as indicated by the coincidence score of 0.013. There are also high degrees of overlap between the condition sets, implying that these conditions can combine to produce high MMS usage, to be confirmed in subsequent analysis.

4.4.3 Necessity and sufficiency of conditions in predicting mechanized maize sheller usage

Next, the sufficiency and necessity of the conditions were examined, which help to determine the relationship between individual sets with each other and with the outcome. QCA was used to generate consistency scores for these two conditions. According to Ragin (2006), consistency is a measure of the degree to which a relation of necessity or sufficiency between a causal condition (or combination of conditions) and an outcome is met within a given data set. The upper diagonal of Table 4 represents the consistency scores for sufficiency while its lower diagonal reports that for necessity.

The scores show that high cooperation (D) is the single set that–alone–is most sufficient for predicting the outcome (consistency = 0.656). Better relationship within the sheller groups follows next with a high consistency score of 0.625 and group contribution by 0.618. Regarding necessity, better relationships within groups is the single set that–alone–is most necessary for predicting the MMS usage (consistency = 0.905). This is again followed by rules obedience (0.882) and cooperation (0.859). What these results tell is that cooperation, better relationships and group contributions are core conditions which in existence can contribute to higher usage of the group MMS.

The preceding results all confirm that the condition sets are related, hence the next exercise is to examine their resulting configurations' sufficiency with the group MMS usage variable. In Tables 5, 6, the consistency scores for the retained configurations that satisfy minimum conditions and a set value (0.8) are reported. According to Ragin (2006), a consistency score lower than 0.75 indicates an obvious departure from the set-theoretic relation in question. A significant value of *p* means that the inclusion in Y consistency and the inclusion not-in Y consistency of a particular configuration are statistically different for all configurations in the solution. Each configuration's consistency is displayed, as well as the resulting test against 0.800 set value. The results indicate that eight configurations are significantly more consistent with high MMS usage than 0.800 at the 0.05 significance level. Table 5 for instance indicates that the configuration DeFGHiJl has the highest number of cases (28 farmers) fitting it, while DeFGhijl has the highest Y consistency score but with only two cases. It is possible though that these configurations may logically overlap.

4.4.4 Final reduction test and consistent solution

To find a consistent solution, the reduction test was reported. The results for the reduction test in Table 7 show that the eight initial configurations have been collapsed into just two, which are DeFGHijl and DeFGHiJl. Based on the reduction test, there are two causal pathways to higher usage of the group sheller. The first causal pathway consists of high cooperation (D), low manual shelling (e), high rules obedience (F), better relationships within groups (G), low prior notice (h), low contribution to group decisions (i), low group contribution (j), and low levels of conflicts (l). The second causal pathway consists of high cooperation (D), low manual shelling (e), high rules obedience (F), better relationships within groups (G), high prior notice (H), low contribution to group decisions (i), high group contribution (J), and low levels of conflicts (l).

The six conditions that are key to higher usage of the mechanized group sheller, *vis-a-vis* its sustainability, are high cooperation within the sheller groups (H), low usage of manual shelling (e), obedience to rules in the constitutions (F), maintaining better relationships within groups (G) low contribution to group decisions (i) and low level of conflicts within groups (l). When these base sets exist, usage of the group sheller is likely to be high. The conditions sets relating to prior notice (H) and group contribution (J) seem to be not so crucial, as the presence or absence of these sets combined with the base sets still produce the same outcome. These two conditions can thus be considered as necessary but not sufficient for high usage of the group sheller.

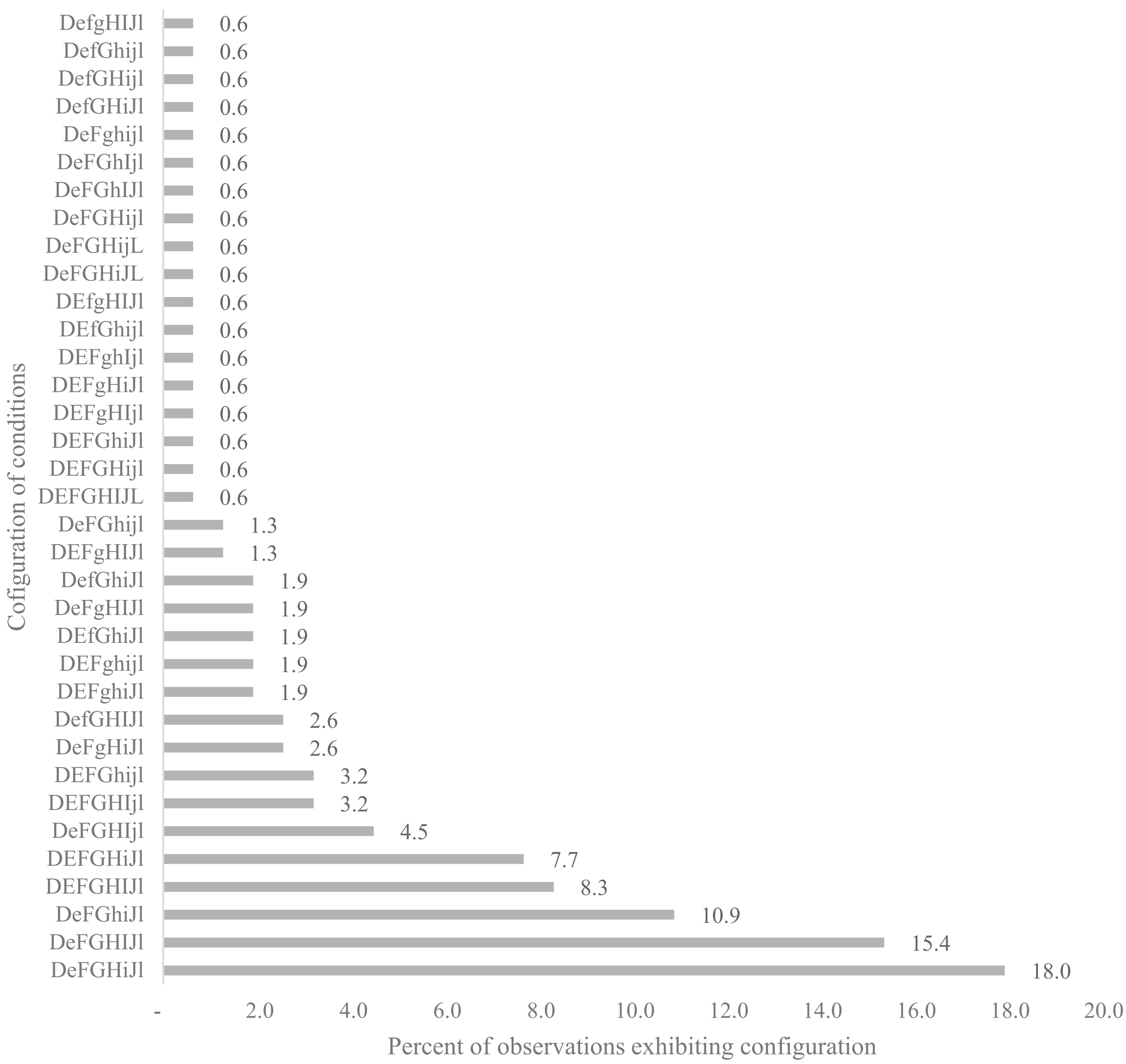

FIGURE 2
Configurations with greater than 0.50 membership. D, high cooperation; d, low cooperation; E, high proportion of harvest shelled manually; e, low proportion of harvest shelled manually; F, perception that members obey constitutional rules; f, perception that members disobey group constitutional rules; G, perception of good relationship among group members; g, perception of poor relationship among group members; H, members are pre-informed of group meetings; h, members are not pre-informed of group meetings; I, members actively contribute to group decision-making; i, members do not actively contribute to group decision-making; J, members honor their financial obligations; j, members do not honor financial obligations; L, high conflicts among group members; l, low conflicts among members.

TABLE 3 Coincidence matrix.

	Y	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*L*
Y (MMS usage)	1.000								
D (cooperation)	0.592	1.000							
E (manual shelling)	0.443	0.568	1.000						
F (rules obedience)	0.544	0.724	0.644	1.000					
G (relationships)	0.586	0.693	0.644	0.786	1.000				
H (prior notice)	0.488	0.597	0.473	0.709	0.676	1.000			
I (group decision)	0.282	0.369	0.250	0.404	0.389	0.534	1.000		
J (group contribution)	0.545	0.646	0.558	0.725	0.727	0.681	0.360	1.000	
L (conflict)	0.013	0.016	0.009	0.021	0.022	0.027	0.015	0.016	1.000

TABLE 4 Sufficiency and necessity matrix.

	Y	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*L*
L (conflict)	0.406	0.664	0.292	1.000	1.000	1.000	0.333	0.667	1.000
J (group contribution)	0.618	0.778	0.260	0.895	0.879	0.774	0.403	1.000	0.016
I (group decision)	0.535	0.776	0.318	0.908	0.862	0.954	1.000	0.769	0.015
H (prior notice)	0.599	0.778	0.287	0.929	0.885	1.000	0.549	0.850	0.027
G (relationships)	0.625	0.779	0.274	0.896	1.000	0.741	0.415	0.807	0.022
F (rules obedience)	0.587	0.786	0.313	1.000	0.864	0.750	0.421	0.793	0.021
E (manual shelling)	0.402	0.928	1.000	0.925	0.779	0.683	0.435	0.679	0.018
D (cooperation)	0.656	1.000	0.361	0.902	0.862	0.720	0.413	0.791	0.016
Y (MMS usage)	1.000	0.859	0.205	0.882	0.905	0.726	0.373	0.823	0.013

TABLE 5 Y-Consistency vs. N-Consistency.

Set	Y consistency	1-Y consistency	*F*	*P*	*N* (Best Fit)
defGhiJl	1.000	0.300	12.23	0.001	0
deFGHiJl	0.878	0.428	13.66	0.000	0
DefGhiJl	1.000	0.242	20.31	0.000	3
DefGHIJl	0.883	0.361	4.18	0.043	4
DeFGhijl	0.995	0.344	9.78	0.002	2
DeFGhiJl	0.796	0.256	8.00	0.005	17
DeFGHijl	1.000	0.217	10.59	0.001	1
DeFGHiJl	0.918	0.209	70.73	0.000	28
DeFGHIjl	0.892	0.418	6.08	0.015	7

Based on the coverage parameters in Table 7, there is low coverage (0.029) for the first configuration (DeFGhijl), which indicates that the cases (number of farmers) exhibiting this causal condition only form about 3 % of the sample and do not represent a large proportion of the cases exhibiting the outcome (high group MMS usage). On the other hand, the second configuration (DeFGHiJl) exhibits relatively high coverage of about 24 percent, indicating that the cases exhibiting this causal condition represent a large proportion of the cases that exhibit high group MMS usage. Thus, the second configuration is more plausible to generate higher usage of the group sheller for a large proportion of farmers than the first.

5 Discussion

The arduous task of manual maize shelling prompts farmers to seek mechanized solutions through collective action (Fischer et al., 2021; Kotu et al., 2023). Factors influencing collective action success are intricate; some conditions aiding success in one context may lead to failure in another (Poteete and Ostrom, 2004). For instance, Gavrilets (2015) discusses free-riding problems and within group heterogeneities, while others point to the adverse implications of group size on collective action success (Ostrom, 1986; Esteban and Ray, 2001; Fujiie et al., 2005). Contextual aspects, such as demographics, collective goals, and guiding institutions, shape collective action outcome (Abdul-Rahaman and Abdulai, 2020; Zang et al., 2022). This study assesses contextual factors for sustaining a mechanical maize sheller intervention among smallholder farmers in northern Ghana using QCA. The study's main hypothesis centered on MMS usage as pivotal for sustainability, generating funds for operational costs and future investments.

Five key conditions–group cooperation, member relationships, individual contributions, rule adherence, and meeting notifications–emerged as essential pathways to increase usage of the group sheller. These findings support existing literature emphasizing cooperation's significance in collective action success (Dong et al., 2018; Ureña et al., 2019; Nayak et al., 2020; Van de Brake et al., 2020).

High levels of cooperation often stem from a strong sense of trust among group members, and this remains crucial for successful collective action (Bakir et al., 2020). Cooperation encourages active participation in group activities, including the use of the group sheller for maize processing. This synergy innures to learning among group members, as argued by Orsi et al. (2017), and demonstrates effective collaboration and inclusive decision-making, valuing diverse opinions and shared responsibilities (Bakir et al., 2020). Conversely, low cooperation, as noted by Jagers et al. (2020), can lead to defection and negative impacts on group performance. Moreover, positive member relationships foster a sense of belonging, motivating individuals toward collective goals rather than individual gains (Fraser et al., 2019).

Group financial contributions play a pivotal role in boosting group funds and maintaining the operational efficiency of the mechanical group sheller, thereby ensuring sustained functionality and productivity. Regular maintenance of the sheller prevents frequent breakdowns, mitigating farmer disillusionment and discouragement from utilizing the group sheller, potentially resorting to manual shelling. Willer (2009) notes that groups reward an individual's financial sacrifices to the group, while Fischer and Qaim (2014) concludes that reciprocity motivates individuals to contribute to group goals. Individuals acknowledging the value of their contributions to group capital formation is essential for group capital formation, providing instrumental capacity to the group's sheller maintenance.

Compliance with constitutional rules within the group context plays a pivotal role in stimulating various aspects that are fundamental to sustained collective action. As highlighted by Markelova et al. (2009), adherence to these rules increases group security by establishing a structured framework that promotes orderliness, consistency, and predictability within the group's operations. By strengthening credibility, obedience to group rules

TABLE 6 Y-Consistency vs. Set Value.

Set	Y consistency	Set value	*F*	*P*	*N* (best fit)
deFghiJl	0.992	0.800	1198.72	0.000	0
deFGHIjl	0.940	0.800	11.92	0.001	0
dEFghiJl	0.928	0.800	8.23	0.005	0
DefGhijl	0.994	0.800	1107.24	0.000	1
DeFghijl	0.892	0.800	4.62	0.033	1
DeFghiJl	0.987	0.800	1841.07	0.000	0
DeFGhijl	0.995	0.800	3410.93	0.000	2
DeFGHiJl	0.918	0.800	11.15	0.001	28

TABLE 7 Final reduction set.

Sets	Raw coverage	Unique coverage	Solution consistency
DeFGhijl	0.029	0.029	0.995
DeFGHiJl	0.237	0.237	0.918
Total	0.266		0.926

increases the trust and reliability members have in the group's functioning, thereby consolidating their commitment to collective initiatives such as the utilization of the group sheller. Moreover, observing these rules fosters uniformity among members, creating a common ground and shared understanding of expected behaviors and responsibilities. This harmonization of conduct cultivates a cohesive environment where members are aligned in their approaches and actions, ultimately contributing to the pursuit of collective objectives. In essence, general adherence to group rules not only signifies a high level of cooperation but also acts as a catalyst for promoting harmonious interactions, facilitating equitable access to shared resources, and consolidating efforts toward achieving collective goals within the group context.

Providing advance information to members about forthcoming group meetings is a crucial factor in nurturing increased usage of the group sheller. Poteete and Ostrom (2004) highlight the significance of adequate information dissemination, emphasizing that a lack of such communication tends to impede coordination and obstruct the attainment of shared objectives within collective endeavors. Offering advance notice of meetings underscores the value placed on members' participation and contributions to collective decision-making aimed at achieving common goals. This proactive communication serves as a foundation for fostering an inclusive environment where each member feels valued and engaged in the collective decision-making process. By informing members beforehand, it acknowledges their importance and encourages active involvement in shaping the direction of the group's initiatives. Consequently, this practice not only cultivates a sense of ownership and accountability among participants but also reinforces a shared commitment toward the group's objectives, such as sustaining the use of the group sheller. Ultimately, prior information dissemination plays a pivotal role in enhancing collaboration, cohesion, and the collective success of the group's endeavors (Poteete and Ostrom, 2004).

In human interactions, conflict can scarcely be ruled out (Rahim, 2023). The absence of conflict within the group setting emerges as a significant factor encouraging the utilization of the group sheller. Conflict, as highlighted by Roskosa and Rupniece (2016), tends to undermine cooperative efforts, ultimately impeding the group's ability to effectively execute shared tasks. Therefore, a low level of conflict becomes a necessary condition for fostering an environment conducive to utilizing the group sheller. Reduced conflict levels signify an atmosphere characterized by mutual respect, peace, and cooperation among group members. This harmonious environment promotes a sense of belonging and unity, motivating individuals to engage positively and actively in collective activities, such as utilizing the group sheller. As the saying goes, "you go where you are celebrated rather than tolerated," indicating that a conflict-free environment encourages active participation and support for shared initiatives.

Furthermore, while individual contributions to group decisions indicate an interest in achieving collective goals, an excessive number of contributions, particularly those that are repetitive or irrelevant are costly (Zhang et al., 2019) and may impede progress. It may lead to extended meeting durations, hindering the establishment of cohesive and forward-moving collective goals within stipulated timeframes. In response, members might choose to limit their active participation in decision-making processes, allowing the constitutional rules to guide proceedings, thereby streamlining discussions and ensuring productive outcomes within the group. Hence, the absence of conflict, balanced participation in group decisions, and a reduction in manual shelling of maize emerge as essential conditions that promote a conducive environment for the successful utilization of the group sheller among the collective.

The necessity of reducing manual shelling of produce cannot be overstated in ensuring the sustainability of the intervention. The continuous reliance on manual shelling practices poses a significant threat to the viability of the group maize sheller. Should farmers persist in manually shelling their produce, the maize sheller within the collective could lose its relevance or even face potential disuse. Consequently, the identification of a low proportion of total output being shelled manually as a vital condition for high utilization of the group sheller is reassuring. Low reliance on manual shelling signifies a higher adoption rate of the mechanized sheller among group members (Kotu et al., 2023). This increased utilization is pivotal as it directly influences the efficiency and cost-effectiveness of the shelling machine. When a substantial portion of produce is manually shelled, it compromises the efficiency gains offered by the shelling machine. This situation may hamper the generation of sufficient funds required for servicing and maintaining the sheller. Ultimately, this could lead to a decrease in the quantity shelled by the machine, further exacerbating the sustainability concerns surrounding its functionality within the collective.

Summarizing, the crucial combination of conditions that collectively ensure high usage of the group sheller, thereby securing its sustainability, includes several key factors: strong group cooperation, minimized manual shelling of produce, adherence to constitutional rules by members, fostering positive relationships within groups, limited contributions to group decisions by members, and reduced conflicts within groups. With these conditions coexisting, the future prospects for the sustainability and potential expansion of the group sheller intervention appear promising.

While the results underscore the impacts of certain conditions on group sheller usage and sustainability, one caveat is the failure of QCA to clarify correlation between variables, hence its inability to quantify how changes in the independent variable (i.e., the causal conditions) affect the dependent variable (Cunha et al., 2023). Nevertheless, QCA explains the logical relationships between the conditions, determining whether they are necessary or sufficient to produce the outcome. Secondly, due to low case counts in the QCA methodology, subjectivity in case selection, conditions and indicator choices could exist (Rihoux et al., 2013). This study preselected cases from the collective action groups, thus precluding theory-based case selection. Accordingly, the claims for generalizability cannot be guaranteed. Nevertheless, the survey design was adequately informed by the collective action theory. The study sample was also randomly generated, thus reducing the risk of subjectivity. Additionally, a 156-farmers sample is comparatively large in QCA context. These strategies are expected to minimize the subjectivity and small sample size risks potentially affecting the results. While QCA does not establish direct cause-and-effect relationships in the traditional sense, its ability to identify necessary and sufficient conditions offers a nuanced understanding of the complex interplay of factors contributing to observed outcomes within specific contexts. This depth of analysis provides valuable insights into the multifaceted nature of social phenomena, contributing to a more holistic understanding of causal mechanisms.

6 Conclusion and recommendation

This paper uses the qualitative comparative analysis (QCA) methodology and data from the Africa RISING project to highlight the contextual conditions that enhance the success of smallholder maize shelling mechanization through a collective business model. The study used the proportion of maize output harvested in 2020 cropping season that was shelled using the mechanized maize sheller as the explained variable, and eight other causal conditions as the explanatory variables. Findings of the study indicate that group cooperation is the single most important sufficient condition that can foster increased usage of the group MMS. Additionally, good relationships among members, payment of financial contributions, provision of prior notice to group meetings and obedience to group rules are important complementary sufficient conditions.

These findings suggest that group members need to understand and respect individual differences, value the opinions of other members and assume shared responsibilities in order to improve cooperation and establish better relationship for a sustainable collective action. Also, the fulfillment of financial obligations is key in augmenting group capital that can be used for maintenance of the mechanized sheller and onboarding of other important interventions that may strengthen their membership and foster the sustainability of the group.

The role of proactive leadership in collective action is key; therefore, it is important that group leaders take proactive steps to always provide prior notice to all members before major group decisions. Further, reduced manual shelling is very necessary for group sheller usage. Hence, leaders must ensure that the mechanical maize sheller remains in well-functioning modes to discourage farmers from manually shelling their produce, as this would retard group success in terms of usage of the group sheller. Finally, as the findings reveal that the absence of conflict enhances success and sustainability of collective action, it is further suggested that group leaders as well as members desist from engaging in actions that may generate conflicts.

In addition to the caveats already outlined, this study requires further cross-validation to improve the reliability and confidence of the empirical findings. Currently, studies addressing this topic are limited, which restricted the depth of discussion. A complementary study applying econometric procedures to assess the QCA-identified configurations might allow the results to be comprehensively scrutinized. These limitations notwithstanding, this study provides valuable insights into the factors influencing group sheller usage. Future research should consider the importance of socioeconomic variables and explore other analytical procedures that can help increase the understanding of the collective actions and their outcomes.

Data availability statement

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

Ethics statement

The studies involving humans were approved by International Institute of Tropical Agriculture. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because most of the participants in the interviews were illiterate to provide written consents. However, they have provided oral consents.

Author contributions

IA: conceptualization, methodology, formal analysis, writing–original draft, and writing–review and editing. BK: conceptualization, data curation, and writing–review and editing. BB: data curation and writing–review and editing. JB: writing–review and editing and formal analysis. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1228382/full#supplementary-material

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