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Sustainable soil fertility practices for smallholder farmers

Edited by
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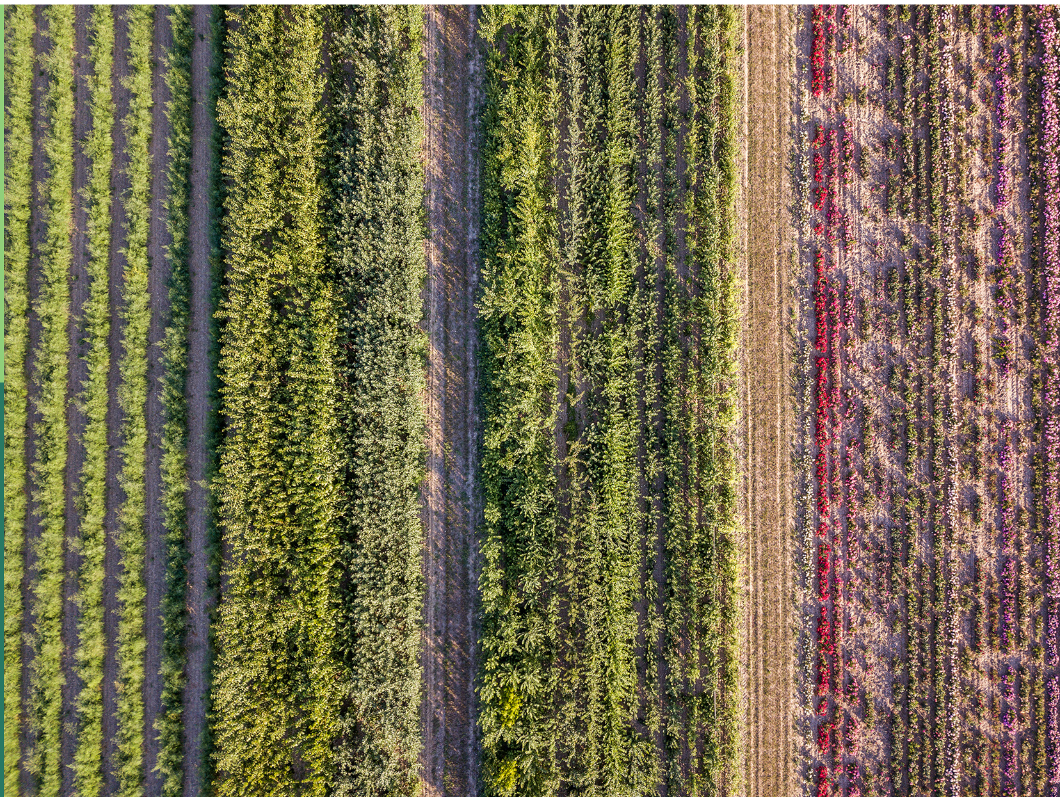

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Sustainable soil fertility practices for smallholder farmers

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Editorial: Sustainable soil fertility practices for smallholder farmers

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Editorial on the Research Topic
Sustainable soil fertility practices for smallholder farmers

Introduction of improved farming technologies to the resource constrained farmers was meant to increase the agricultural output by use of improved and high-yielding farming systems. These smallholder farmers contribute significantly toward food security in the developing countries, so their production methods and output are of concern to food security. However, these newly introduced technologies are high input systems and do not sync with the majority of smallholder farmers in the developing countries. Hence, productivity is still low among smallholder farmers due to the high financial investment per season required for these improved technologies. One of these technologies that smallholder farmers have adopted is the use of synthetic fertilizers, that mainly feeds the crop whilst not feeding the soil, which has driven soil degradation among the smallholder farmers. Furthermore, most of these smallholder farmers use these fertilizers at sub-optimal levels, which has further driven nutrient mining. Therefore, this Research Topic focused on compiling current research on sustainable soil fertility management practices and technologies that are applicable to resource poor smallholder farming systems. Published articles from this topic can be grouped into four sub-themes as follows:

Conservation agriculture

Conservation agriculture (CA) is one of the affordable soil fertility management practices among the smallholder farmers. The CA has offered numerous socio-economic and environmental benefits to the smallholder farmers. Climate change is real and leading to low productivity through recurrence of droughts and shifting of planting dates to mention a few. However, the adoption of CA and climate-smart agriculture (CSA) technologies can be a panacea to the negative impacts of climate change and low fertility among the smallholder farming systems. The CSA technologies have been widely promoted among the smallholder farmers, unfortunately there is marginal adoption or dis-adoption due to wrong designing and implementation of such technologies. In a way to understand causes of the low adoption, Musara et al. assessed the impact of adopting farmer-oriented CSA practices combined with hybrid sorghum variety and partial-organic fertilizer on household income and productivity. A set of farm specific factors such as arable land and off-farm factors were noted to influence the decision to adopt CSA technologies. Therefore, it is essential to design farmer-imitated CSA practices that will be easier to adopt unlike practices generated outside the farmers' context. The end-users (farmers) should be therefore included during the designing phase of the sustainable soil fertility management practices and technologies to allow easy implementation.

The CA is a viable technology for ameliorating the low soil fertility among the smallholder farmers, especially in the developing countries like Zimbabwe, Malawi and South Africa. Chauke et al. explored how no-till and varied P fertilization can be used to improve soil properties. Soils in the smallholder farming systems are usually low in available phosphorus (P) and poor utilization efficiency of applied P which negatively affect crop production. In this regard, Chauke et al. hypothesized that addition of phosphorus, growing of high-yield varieties and suitable cropping systems can enhance crop productivity under dryland conditions. Briefly, two tillage systems [no-till (NT) and conventional tillage (CT)], three varieties, and three phosphorus rates (0, 30, and 60 kg/ha) were evaluated for soybean productivity. The P uptake was increasing with P application rates. The grain yield was high at 30 kg/ha P application under NT but varied with variety. Nevertheless, high availability of soil P lowered the soybean oil content and increased protein content, activities of acid phosphatase (ACP) and alkaline phosphatase (ALP). Conclusively, addition of P fertilizers to appropriately selected crop varieties can improve both quantity and quality of the crop. The smallholder farmers should use no-till with optimum fertilizer application rates so as to maintain ideal soil fertility status at their farms.

The smallholder farmers can change their production model from non-cyclic conventional agriculture to conservation agriculture (CA). However, the change has yield penalties so farmers are reluctant to take the risk. Quantification and of the yield penalties especially at the early transition stage to CA is necessary. Knowing the amount of yield reduction incurred during the conventional to CA transition is crucial for decision making especially in cash crop production. Yemadje et al. studied the combined impact of no tillage (NT) and different fertilizer application rates on cotton agronomic performance in cotton-cereal rotations. This study applied multilocation experimentation in three-different agroclimatic zones. Three different forms of soil preparation (tillage: strip tillage, and no tillage or direct seeding) and four fertilization regimes at these sites were evaluated. Direct seeding reduced below-ground biomass growth and seed cotton yields in an early transition to CA. Yemadje et al. recorded limited yield penalties in the studies cotton-cereal rotations which suggested that if well planned, the transitional phase from the conventional tillage to CA may not be very costly in terms of yield reduction to the smallholder farmers. Therefore, sustainable soil fertility management practices in the context of degraded soils and poor productivity are required among the smallholder farmers. Farmers are willing to change to CA if low yield penalties are reasonable trade-offs especially in the early years of a transition.

Intercropping and productivity

Good agronomic practices are also essential in enhancing soil fertility among the smallholder farmers. In this regard, Dzvene et al. carried a 2-year study to determine effects of intercropping sunn hemp (*Crotalaria juncea* L.) into maize (*Zea mays* L.) at different time and densities on productivity under rainwater harvesting technique. The study had three sunn hemp planting times which were intercropped at different maize growth stages (simultaneous, early and late vegetative). Generally, the growing season conditions were affected by the rainfall distribution. The planting period affected the biomass production of the sunn hemp which was highest when intercropped at early maize vegetative stage. Additionally, Dzvene et al. found that incorporation of sunn hemp at early maize vegetative stage had economic benefits by having a high-income equivalent ratio which translated to income. Inclusion of sunn hemp at early maize vegetative stage was an ideal for the smallholder farmers under rainfed conditions as it increased the economic benefits in a sunn hemp-maize intercrop.

In another study, Ekyaligonza et al. looked at strategies to improve soil health through increasing soil organic matter (SOM). The smallholder farmers can use sustainably cheap and environmentally friendly soil fertility management options e.g., the farmyard manure, cereal-legume intercropping and crop residue mulch cover to increase their agricultural productivity (Ekyaligonza et al.). Regrettably, there is limited information on the economic benefits accrued from these strategies by the smallholder farmers, hence their low adoption. Interestingly in this unique article, Ekyaligonza et al. noted similar accrual of farm revenues and gross margins for synthetic fertilizer plus maize monocrop and from various organic matter management (OMM) strategies. Hence integrating the OMM strategies in smallholder farming systems can increase farm income. The price sensitivity analysis showed that farmers should also include at least two legumes in their cropping rotations so as to achieve high socio-economic benefits.

Inappropriate crop management practices are a common problem causing reduced agricultural productivity among the smallholder farmers. Crop management practices like incorrect planting time, fertilizer application rates, weeding time etc are some of the common malpractices among the smallholder farmers. Awio et al. concluded that improved agronomic management resulted in improved crop yield. According to Awio et al., the farmers who used the recommended agronomic practices (RAP) but were lower-yielding under farmers' practice (FP) got improved yield, compared to both the middle- and top-yielding farmers prior to the adoption of the RAP. This suggests that there will be increased crop productivity among smallholder farmers if they can adopt standard crop management practices.

Sustainable soil fertility amendments

Dryland agriculture is common among the smallholder farming systems unfortunately with low productivity. Mataranyika et al. reviewed how natural existing plant microbe interactions can increase dryland agriculture productivity in the context of Namibian climate and soil profiles. These interactions have some microbes such as bacteria which can promote plant growth and with extensive research can be a potential form of sustainable soil fertility management under the dryland agriculture that also reduces the impact of agriculture on climate change. According to Mataranyika et al. these plants associated bacteria used to develop biofertilizers which are both economically and environmentally sustainable while increasing soil health and crop yield. Besides being biofertilizers, these microbe-plant interactions produce essential biochemicals and enzymes e.g., indole-acetic-acid (IAA) and amino cyclopropane-1-carboxylate deaminase. They can also improve the plant health by actively protecting plants from pathogens e.g., fungal pathogens. Regardless of all these potential benefits, such interactions have not been fully exploited especially under the smallholder farming systems. Low land productivity is another constraint that causes low crop yields in dryland agriculture. In order to avert this situation, Pierre Tovihoudji et al. worked on hill-placement of microdose biochar-compost-based amendments on agronomic and economic performance of cotton in Northern Benin. The biochar-compost-based amendments are carbon-rich hence can sustainably improve soil health by increasing the soil organic carbon (SOC) content. The SOC is proportional correlated soil productivity so the cotton yield was improved by >86% under the biochar-compost-based amendment compared to absolute control without any amendments. The biochar-compost-based amendments also enhanced the cotton economic performance. Measured value Cost Ratio (VCR) and Benefit Cost Ratio (BCR) values under the organic rich soil management practices were better than in mineral fertilized soils. Therefore, use of mineral fertilizers alone as the common practice among smallholder farmers has no economic advantage hence not a sustainable soil fertility management strategy among the resource constrained smallholder farmers.

Soil degradation

Land degradation is one of the major causes of low soil productivity among the smallholder farming systems in the developing countries. Therefore, to achieve a sustainable improvement in soil productivity, protecting cultivated land from any form of degradation is mandatory among the smallholder farmers. Land protection and enhancing its quality should be carefully implemented in order to reduce ecological and environmental pressure which lead to land sustainability. According to Xu et al. it was necessary to know the differences and causes of cultivated land protection behavior (CLPB) between different sets of farmers (i.e., smallholder vs. professional farmers) because this will assist in the formulation of effective targeted protection policies on the management of agricultural lands. This study used survey data obtained from 422 mango farmers in Hainan province, China where internal and external characteristics between the two different sets of farmers were explored. Cultivated land protection behavior between the sets of farmers was different and sources of differences in CLPB between the farmers was also different. Interestingly, the internal characteristics of the farmers had more influence to the cause of the differences in CLPB of the farmers. It is therefore important to design separate land protection policies for the smallholders and professional farmers so as to achieve sustainable land management practices.

Accelerated soil erosion is the worst form of land degradation among the smallholder farming systems. Rates of soil erosion are very high among these smallholder farmers and negatively impact on the soil productivity through loss of soil fertility. Ineffective control of the soil erosion is a persistent problem among the smallholder farmers. In the last published article, Tibassima et al. aimed at re-aligning soil erosion management toward a nature-society-inclusive strategy. The study hypothesized the effective control of soil erosion is increasingly require bridging the mismatch between science, policy, and practice. The issue of soil erosion control goes beyond the understanding it as an assemblage or hybrid of biophysical and anthropogenic facets but also an epistemology that brings the scientists, policymakers and farmers to a common understanding. Tibassima et al. tested a newly proposed hylomorphic (disaster risk management) framework as a sustainable soil erosion management strategy. Briefly, the framework structures the procedure of bridging lived experiences of those at risk with theoretical knowledge so as to co-create knowledge and co-designing options for managing soil erosion. Interesting this study is the first to test the new framework in a case of soil erosion where it confirmed that lived experiences exposes blind spots in understanding the local context of soil erosion. The lived experiences also flatten the ontology-specific epistemology toward a more nature-society-inclusive soil erosion management strategy among the smallholder farming communities.

Hopefully these published articles are going to impact to a wide range of readers with an insight into practical sustainable soil fertility management and technologies among the smallholder farming systems.

Author contributions

CP: manuscript drafting and final write-up. AM, HM, and RM: manuscript review and final write-up. 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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Rethinking Blended High Yielding Seed Varieties and Partial-Organic Fertilizer Climate Smart Agriculture Practices for Productivity and Farm Income Gains in the Drylands of Zimbabwe

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Most blended climate smart agriculture (CSA) technologies focusing on seed-fertilizer combinations have either been marginally adopted or dis-adopted by smallholder farmers due to the nature of design and implementation. A data science research approach was used with 380 households in the mid-Zambezi Valley of Zimbabwe. The study examines impact of adopting a farmer initiated CSA practice combining improved sorghum seed variety and partial-organic fertilizer on household income and productivity among smallholder farmers in the drylands of Zimbabwe. A cross sectional household survey using multi stage sampling with purposive and stratified proportionate approaches was conducted. A structured questionnaire was utilized for data collection. Endogenous Switching Regression (ESR) model was utilized to account for self-selection bias of sampled farmers. Overall, a combination of farm specific factors (arable land, variable costs) and external factors (distance to the market, value of aid) have a bearing on the adoption decision and the associated impact on productivity and income. The counterfactual analysis shows that farmers who adopt the technology are relatively better off in productivity and income. Our findings highlight the significance of improving access to CSA practices which are initiated by the farmers using a bottom-up approach since they suit their operating contexts better. Tailor-made supporting programs including farmer networking platforms and decentralized markets need to be designed and scaled up by policymakers to encourage farmers to adopt blended soil fertility CSA practices in their farming practices. Networking arrangements need to be strengthened through local, government and private sector partnerships along the sorghum value chain.

Keywords: climate smart agriculture, farmer-centric technology, agricultural productivity, Zimbabwe, endogenous switching regression, counterfactual

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THE BACKGROUND

The dominance of inappropriate agricultural practices such as improper soil preparation and management, indiscriminate use of pesticides and application of chemical fertilizers beyond the limit has persistently caused a range challenges including decrease in crop yields, soil erosion, soil salinity and pollution of water bodies. In southern Africa's agricultural value chains, this matrix of problems has culminated in reduced productivity across strategic cereal crops such as maize (*Zea mays*), sorghum (*sorghum bicolor*) and millets from on average 1.3 tons/ha to 0.9 tons/ha and lowered income by on average 23% due to a decline in the weighted average prices by 19.2% between 2015 and 2019, especially among smallholder farmers (Suresh et al., 2021). To circumvent this array of problems, there is an emerging drive toward co-designing a diverse range of resilient CSA programs with a focus on farmers taking the center stage. Climate-smart agriculture is defined as integrated pathway that enhances the management of landscapes including the cropland, livestock systems. The advent of re-orienting CSA programs has variably pushed the design and scaling up of blended modern science and Indigenous Knowledge Systems (ITK) packages across different spatial and temporal scales (Nciizah et al., 2021). These blended CSA packages entail a combination of CSA principles in a way that direct response to the context specific challenges such as access to and application of chemical fertilizers. The core CSA practices included in these blended packages include efficient irrigation, integrated pest management (IPM), different dimensions of conservation farming and manipulation of seed and other production factors such as the use of manure (Sinyolo, 2020). Globally, therefore, the adoption of climate smart agriculture (CSA) practices is also widely reported as a gateway out of the challenges of low productivity and income among smallholder farmers in the climate change exposed drylands (Kauma, 2021; Martey et al., 2021).

In the drylands of Zimbabwe, these emerging CSA strategies have however over focused on the more preferred cereal crops including maize and cash crops such as cotton (*Gossypium*) (Mkuhlani et al., 2018). Of note, are the traditional grains, including sorghum and millets, that have not been adequately and directly accommodated at all scales (Hamukwala et al., 2010; Adegbola et al., 2013; Musara et al., 2018). However, pushed by exponential decline in agricultural performance in these fragile communities and increased incidences of income deterioration, a handful of the emerging CSA interventions targeting the peripheral crops, such as sorghum seed development, financing, production and marketing support programs have been implemented by the public and private sectors post 2010 (Mapfumo, 2017). The hope is that these direct mechanisms as mentioned above will enhance sorghum productivity and income through scaled up adoption of tailor-made CSA technologies and strengthening market linkages at the different administrative, spatial and temporal scales. The acknowledgment is that, re-embracing these orphan crops and greasing their production with appropriately designed farmer-centric and market oriented CSA practices can reposition them in land allocation decisions especially in the drylands (Muzerengi and Tirivangasi, 2019).

Most of the aforementioned interventions have been designed based on a top-bottom approach, and as such, in most countries including Zimbabwe, their effectiveness has been relatively below the expectations in terms of productivity, income and food security gains (Mapfumo, 2017). This has induced lower than expected adoption with on average 30% of farmers taking up the technology against a target of above 80% (Shiferaw et al., 2013). On one hand, smallholder farmers cultivate the crops on small pieces of unproductive land averaging 0.15 hectares against an expected benchmark of 0.3 hectares, while also using low yielding varieties and recycled seed (Khonje et al., 2015; Mujeyi et al., 2021). On the other end, sorghum processors and consumers are not willing to pay competitive market prices and pay on average 11.3% below the breakeven price for the produce, thus further reducing the utility and subsequent adoption (Makindara et al., 2013). The result is that in most parts of dryland southern Africa, comprehensive understanding of the productivity and income enhancing capacity of emerging blended CSA based sorghum production practices is therefore presently missing and/or inadequately explored (Tambo and Mockshell, 2018).

There is evidence that, in southern Africa, there is a pattern where smallholder farmers are adopting a package of technologies as opposed to singular adoption which dominated during the early 1990s (Mujeyi et al., 2021; Ahmed, 2022; Baiyegunhi et al., 2022). The study seeks to contribute to this discussion by focusing on the blended high yielding seed varieties and partial-organic fertilizer[1] package that has been designed by smallholder farmers in the mid-Zambezi Valley of Zimbabwe in response to the call for CSA. To the best of our knowledge, the complementarity between improved seed and varieties and inorganic fertilizer has not adequately been tapped into from the angle of technology re-design to accommodate emerging commercial organic fertilizers and traditional grains. It remains questionable as to whether there are any productivity and income gains that may be generated from the uptake of the blended and well-targeted improved seed and organic fertilizer.

A number of studies (e.g., Ali and Abdulai, 2010; Di Falco et al., 2011; Asfaw et al., 2012; Suresh et al., 2021) have examined the impact of agricultural technologies on food security and income, but the majority focused on externally driven interventions emanating from either the government, NGOs or the private players. Those which have attempted to accommodate the fertilizer component have focused on the inorganic fertilizers (Ahmed, 2022). This has crowded out a reflection on farming community initiated technologies designed in response to emerging challenges and opportunities. Additionally, most studies targeting traditional grains (e.g., Mapfumo, 2017; Musara and Musemwa, 2020; Phiri et al., 2020), have also focused more on the food

[1]The fertilizer is not purely organic and is produced by a Zimbabwean firm. The package was initiated by farmers in partnership with a NGO and is being promoted in 7 of the 17 wards in Mbire district of Zimbabwe. The blending idea emanated from the farmers and the NGO supports through training programmes. To the best of our knowledge, this farmer initiated technology is a first in the district which targets sorghum production.

security dimension, which does not directly support the industrialization and market based commercialization (with proxies of income and productivity) drive being advocated for by stakeholders in Zimbabwe and analyzed in this study as a gap filling effort. Furthermore, in the existing analyses, sorghum production is traditionally viewed by farmers as a system requiring minimal fertilizers. Phiri et al. (2019) reports that this mentality has subsequently spilled over to the research agenda thus delineating the fertilizer component from impact analyses.

We identify the potential of capturing this missing dimension using sorghum as a pivotal crop in the drylands of Zimbabwe due to its resilience to unfavorable conditions of short growing season, limited rainfall and high temperatures. This is motivated by the success of sorghum value chains in countries such as Tanzania (Makindara et al., 2013), Zambia (Hamukwala et al., 2010) and West Africa (Haussmann et al., 2012) that has been attributed to scaling up of farmer driven productivity-enhancing technologies. In these environments, productivity has increased by on average 34.5%, food security by 29.3% while conflicting findings have been reported for income gains within a range of 12.6-27.1% (Smale et al., 2018). The technology in this study was initiated by the local farmers and culminated in a well-structured improved seed and partial-organic fertilizer package used in the study area over the past 3 seasons. The study therefore aims to fill the gap of productivity and income impact analyses and target a blended soil fertility enhancing strategy for sorghum, which is a largely excluded crop. It further examines the impact of a farmer designed package on productivity and income, a feat that is not adequately covered in literature.

MATERIALS AND METHODS

Description of the Study Site

The study was conducted in Mashonaland Central province which is located at 16.7644° S, 31.0794° E, has an area of 28,347 km², a population of 1,152,520 which represents ∼8.5% of the total Zimbabwe population and has a human population density of 41/km^2 (ZimStat, 2013). The mid-Zambezi Valley of Zimbabwe is situated in the province at an altitude of between 350-600 meters on the flat plain and 1228m on the highest point. **Figure 1** shows the study area.

Mbire district is located in the Lower Zambezi Trans-Frontier Conservation Area (LZ-TFCA), and has multi-cultural communities with a low human development index (HDI) of on average 0.519. Despite poor sandy soils, erratic rainfall (averaging 300mm/annum), high temperatures (averaging 35°C) and persistent crop destruction by wildlife (accounting for more than 35% of field crop losses), households heavily depend on agriculture for subsistence and income. The major activities include crop production of mainly sorghum, cotton, rapoko (*Eleusine coracana*) (in Zimbabwe- finger millet), and pearl millet (*Pennisetum glaucum*), as well as livestock where mainly cattle and goats are reared. These integrated production systems marginally reduce the risks of extreme poverty but are however not commercialized and linked to strategic markets in surrounding towns such as Mvurwi (17.0278° S, 30.8556° E).

Data Type, Sources, and Sampling Design

A pragmatic philosophy was adopted for the study and merged both the explanatory and exploratory research approaches in a cross sectional survey design. Specifically, the study was conducted in Mbire district of Mashonaland Central Province in Zimbabwe. The district was selected since it is a dryland located in the dryland region IV and V, which receives low and erratic rainfall coupled with high temperatures. A number of climate smart agriculture practices including soil fertility enhancing options, water conservation pits and inorganic fertilizer programs have also been widely supported by the government, Non-Governmental Organizations and the private sector players. From the seventeen wards in the district, five wards, 2, 4 and 10, 12 and 15 were purposively selected and included in the study. The first four wards are the dominant sorghum producing areas in the district while Gonono and Chikafa are closer to the border with Mozambique and their inclusion offered scope for understanding decisions in communities with mixed cultures and relations. Mahuwe is centrally located in the district while Chisunga (Angwa) is at the periphery of the Mid Zambezi Region. Chitsungo is a unique Ward were sorghum production is minimal and as such would also offer insights into the non-production of sorghum. The data used in the study were collected from a survey conducted during the cropping season between January and March 2020. This was also basing on information gathered from a pre-survey conducted between March and April 2016 and a series of preliminary stakeholder consultation meetings in partnership with the French Agricultural Research Center for International Development (CIRAD). The study adopted a multistage sampling strategy starting with the purposive selection of wards and stratified proportionate selection of villages to account for the adoption and non-adoption variabilities across the villages. This culminated in the proportionate random sampling of respondents from each stratum for the survey.

The Yamane (1967) formula was utilized to determine the sample size given its simplicity and wide application in social science studies. The formula was presented as in Equation (1) below.

$$n = \frac{N}{\left[1 + N\left(e^2\right)\right]} \tag{1}$$

where n is the sample size, N= is the population size, and e is the precision level for confidence interval of 95% (=0.05). This yielded 380 sorghum farmers who were then included in the study. The sample size compares relatively well with other similar studies (e.g., Abdulai and Huffman, 2014). The purposive selection was based on a criteria of guaranteeing the targeting of wards and villages where there was adoption of the targeted package of an improved sorghum seed variety and partial-organic fertilizer, while capturing the diversity of household types, landholdings, access to markets among other key factors. Proportionate stratified random sampling allowed for a representative sample to be generated while accounting for

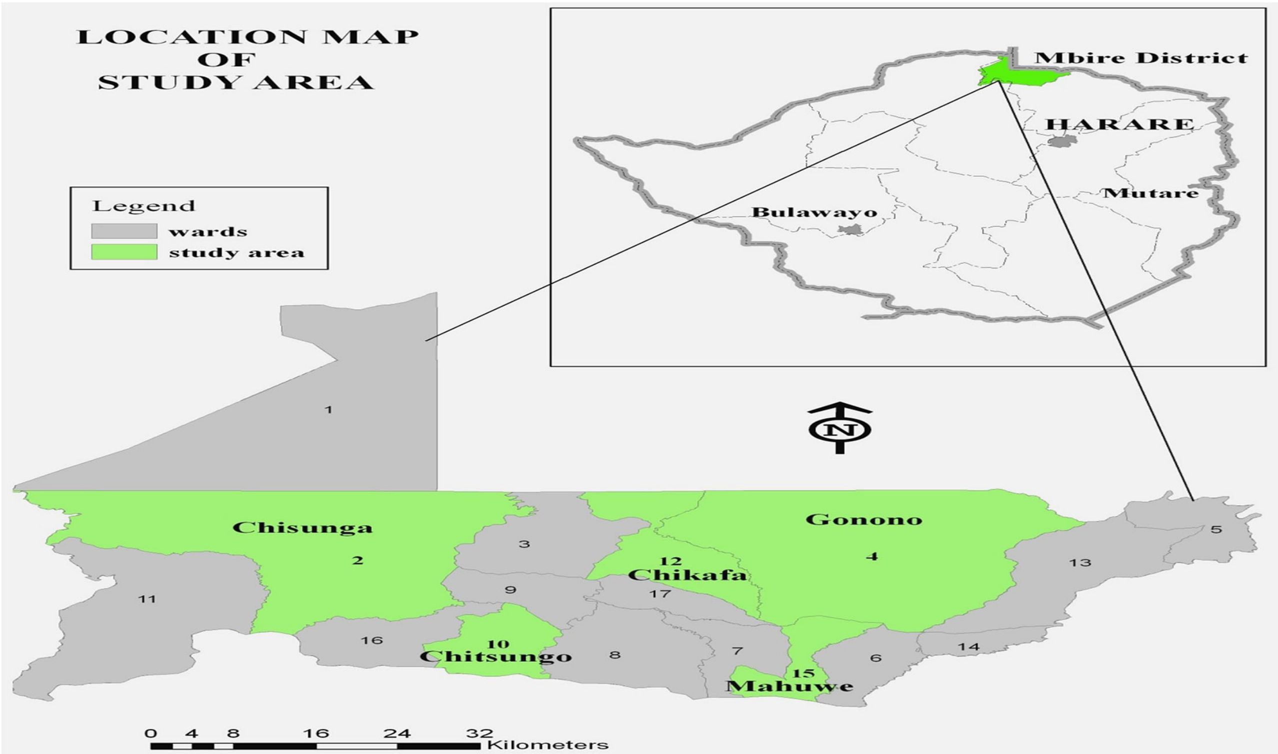

FIGURE 1 | Map showing the study sites.

TABLE 1 | Ward composition and farmer selection.

Ward[a]	Total no. of farmers	Share of farmers (%)	No. in sample
Chisunga (2)	1,580	19.18	73
Gonono (4)	1,911	23.07	88
Chitsungo (10)	1,978	23.88	91
Chikafa (12)	1,587	19.17	73
Mahuwe (15)	1,224	14.70	56
Total	8,280	100	380

[a] *The ward number is placed in parenthesis.*

the differences in farmer compositions across the locations of interest. **Table 1** shows the sampling strategy summary.

Detailed information was generated from the farmers using a standardized questionnaire and validated by discussions with authorities from the Ministry of Lands, Agriculture, Fisheries, Water and Rural Resettlement (MLAFWRR), mainly through local Department of Agricultural and Technical Extension Services (AGRITEX) officers. The collected data covered information on the technology's characteristics, production systems used by farmers, input access and use, transaction costs, market prices, socio-economic characteristics, and plot-level attributes. To cater for the instrument's validity and reliability, a pre-testing process was conducted. The data was captured in the STATA 13 program, cleaned, coded and analyzed.

Method of Data Analysis

Rationally, farmers consider potential benefits when making decisions to adopt emerging agricultural technologies. As such, in impact evaluation studies, researchers need to consider the nature of these technologies and avoid selection bias problems emanating from truncated observed distributions of technology outcomes (Kabunga et al., 2012). The selection bias manifests whenever the unobservable factors influence both error terms in the technology choice equation (ε) and the outcome equation (μ). This results in correlation of the error terms of the two equations, with$corr(\varepsilon, \mu) = \rho$. In this case, utilizing the generic regression techniques such as ordinary least squares (OLS) would generate biased results. Additionally, attempting to estimate the impact of the adoption decision where there is no information on the counterfactual condition would not be useful for influencing policy and practice.

Alternative Estimation Approaches

A number of alternative approaches have been widely used in technology adoption impact analyses. The Heckman two-step method has been used by some authors (e.g., Ghimire and Huang, 2015) to deal with selection bias. The major limitation sets in due to the method's inherently restrictive normally distributed errors assumption. An alternative approach of controlling for selection bias is to utilize the instrumental variable (IV) method. It is however difficult to find and identify valid instruments to include in the estimation. Additionally, in the IV process, as is the case with OLS estimation, the linear functional form assumption does not always hold since the coefficients on the control variables may be different for adopters and non-adopters.

The propensity score matching (PSM) technique has also been extensively used (e.g., Caliendo and Kopeinig, 2008; Becerril and Abdulai, 2010) to balance the observed distributions of the covariates for the non-adoption (control) and adoption (treatment) groups. The main drawback is the Conditional Independence Assumption (CIA), which states that, for selected covariates, the adoption is independent of potential outcomes. However, selection into the treatment group, based on unmeasured characteristics, may also trigger systematic differences between the groups' outcomes, regardless of conditioning on the observables. Using PSM implies that, the estimates from the binary model (probit or logit) cannot be interpreted to imply the determinants of adoption. In the current study, we however intend to determine the adoption drivers of an emerging blended CSA technology package and the associated impact on the productivity and income. To achieve this, we utilized the endogenous switching regression (ESR) model which accounts for the selection bias on estimating the impact of adoption on the two farm outcomes of interest. The method is a generalization of Heckman's selection correction approach and captures the selection on unobservable by treating selectivity as an omitted variable problem (Lokshin and Sajaia, 2004).

The Endogenous Switching Regression Strategy

We used a two-step estimation strategy to fit the ESR model. In the first step, we model farmers' technology adoption decisions using the probit model to generate inverse Mills ratios while accounting for the unobserved heterogeneity (Alene and Manyong, 2007). The relationship that we consider in examining the impact of adoption on the productivity and income assumes a linear function of a vector of explanatory variables, X_i and an adoption dummy variable, A_i. Estimates α_r then represent a model for discrete X_i given as:

$$Y_i = d_{iX} X\beta_X + \alpha_r A_i + \mu_i \tag{2}$$

Where Y_i is the dependent variable (mean of the outcome indicators); β_X is the regression induced effect when $X_i = X$; α_r is the regression parameter; A_i is a dummy variable for the use of the new technology such that $A_i = 1$ if the technology is adopted and $A_i = 0$ when the technology is not adopted and μ_i is a normal random disturbance term. Whether farmers adopt the technology or not is dependent upon the interaction of the characteristics of farmers and farms, hence the adoption decision for the technology package is determined by each farmer's self-selection and not random assignment.

The subsequent outcome equations are then estimated in the second step by factoring in the inverse Mills ratios as an additional regressor to capture selection bias. Following recommendations by Di Falco et al. (2011), we adopted the full information maximum likelihood (FIML)[2] estimation method. This approach simultaneously estimates the probit criterion (selection equation) and the regression equations, thus yielding consistent standard errors. The outcome functions (yield/ha and income/ha) are estimated for adopters and non-adopters separately, thus taking into account the endogenous nature of adoption decisions. The relationship between the outcome variables and exogenous variables X_i for each possible regime is thus specified by the following equations:

$$A_i = 1\ (z_i\gamma + u_i > 0), \tag{3}$$

$$\text{Regime 1: } Y_{0i} = X_{0i}\beta_0 + \varepsilon_{0i} \text{ if } A_i = 0 \text{(no adoption)} \tag{4}$$

$$\text{Regime 2: } Y_{1i} = X_{1i}\beta_1 + \varepsilon_{1i} \text{ if } A_i = 1 \text{(with adoption)} \tag{5}$$

Where Equation (4) is the selection equation denoting the regime that applies, z_i is a $1 \times m$ vector of explanatory variables assumed to explain the adoption probability, and u_i, ε_{0i} and ε_{1i} are the error terms. As farmers' decision of adopting the blended pack can be endogenous, the correlation between error terms ε_{0i} and ε_{1i} based on the sample selection criteria has a non-zero expected value (Abdulai and Huffman, 2014). As such, the parameters (β_1 and β_2) of OLS estimation may produce sample selection bias[3]. Assuming that the three error terms, u_i, ε_{0i}, andε_{1i}, have a trivariate normal distribution with a zero mean, then, the variance-covariance structure is:

$$cov(u_1, \varepsilon_{1i}, \varepsilon_{0i}) = \begin{bmatrix} \delta^2{}_u & \delta_{1u} & \delta^2{}_{0u} \\ \delta_{1u} & \delta^2{}_1 & \delta_{01} \\ \delta_{0u} & \delta_{01} & \delta^2{}_0 \end{bmatrix} \tag{6}$$

Where $\delta^2{}_u$, $\delta^2{}_1$, and $\delta^2{}_0$ are the variances of error terms u_i, ε_{1i}, and ε_{0i}, respectively; while δ_{1u} denotes the covariance of u_i and ε_{1i}; and δ_{0u} denotes the covariance of u_i and ε_{0i}. We also define the ρ as correlations between error terms, for farmers who adopted and those who did not adopt the technology, as $\rho_{1\mu} = \text{corr}(\varepsilon_{1i}, \mu_1)$ and $\rho_{0\mu} = \text{corr}(\varepsilon_{0i}, \mu_1)$. However, given the nature of the sampling, A_{i1} and A_{i0} do not occur at the same time, so the covariance between ε_{i1} and ε_{i0} is uncertain. Based on this assumption, the expected values of ε_{1i} and ε_{0i} can be used to account for the the inverse Mills ratio where $\lambda(\cdot)$ which is defined as:

$$\lambda_1 = \frac{\emptyset(z_i\gamma)}{f(z_i\gamma)}\ if\ (A_i = 1)\ and\, \lambda_0 = \frac{\emptyset(z_i\gamma)}{1 - f(z_i\gamma)}\ if\ (A_i = 0) \tag{7}$$

Where $\emptyset$ and ϕ are the pdf and cdf of the standard normal variable, respectively. When $\rho_1 = \rho_0 = 0$ the endogenous switching regime model equations switch to the exogenous regime model. We recognize that there might be endogeneity of adoption in the outcome. This was partially addressed by including comprehensively selected covariates from literature

[2]The FIML estimates of the parameters of the endogenous switching regression model were obtained using the movestay command in STATA.

[3]This is also known as the problem of missing variables (Lee, 1982).

(Zeng et al., 2015). Additionally, by having a valid instrumental variable that is exogenous, then λ_1 and λ_0 can be obtained from the first stage and included in regimes Equations (3) and (4) (Tufa et al., 2019). For identification purposes, our guiding hypothesis is that the probability of a household to adopt improved technology is an increasing function of its prior exposure reflected by the two selection instruments which are the soil fertility gradient and the storage[4]. Following Di Falco et al. (2011), we determine the acceptability of these instruments by conducting a rejection test of whether they affect the CSA technology adoption decision and not the income and productivity outcome variables among non-adopting households. Results show that the two variables can be considered as valid selection instruments.

In order to examine the effect of adoption on the productivity and income, we utilized the estimated coefficients from the ESR model to compute the average treatment effect (ATE). This defines the difference between the expected values of observed and counterfactual scenarios. In this study, we estimated the average treatment effect on the treated group (ATET) as the difference between Equations (7) and (8). ATET can be effectively used to eliminate the estimation bias caused by observed and unobserved factors and examine the overall effect of adopting the blended pack on farmers' productivity and income. In this regard, we also assume that $E\left(u^2{}_i\right) = 1$, and hence the conditional expectation of the outcome variable in Equations (3) and (4) can be defined respectively as:

$$E\left(Y_{1i}|x_i, A_i = 1\right) = x_i\beta_1 + \rho_1\lambda_1\left(z_i\gamma\right) \quad (8)$$

$$E\left(Y_{0i}|x_i, A_i = 1\right) = x_i\beta_0 + \rho_0\lambda_0\left(z_i\gamma\right) \quad (9)$$

Informed by Paudel et al. (2020) the ATET was calculated using Equation (9):

$$E(Y_{1i}|x_i, A_i = 1) - E\left(Y_{0i}|x_i, A_i = 1\right) = x_i\left(\beta_1 - \beta_0\right) + \rho_1\lambda_1 - \rho_0\lambda_0 \quad (10)$$

We then utilized the Nearest Neighborhood Method (NNM)[5] for mirroring experimental randomization and estimate the effects. In Equations (7–9), the term $E\left(Y_{0i}|x_i, A_i = 1\right)$ is the expected value of Y_i if the household had not adopted the CSA practice. It is the unobserved component which was estimated using counterfactual analysis as guided by Di Falco and Veronesi (2013). The term $E\left(Y_{1i}|x_i, A_i = 1\right)$ denotes the actual expected value of farmers' productivity and income.

RESULT AND DISCUSSIONS

This section presents the findings from the study and the discussion in relation to the existing body of knowledge on the adoption and impacts of agricultural technologies.

Descriptive Analysis

Table 2 shows the descriptive statistics for the sampled households and isolates some important indicators in terms of differences between the adopters and non-adopters.

It can be observed from the table that the farmers who adopted the technology for the 2020 cropping season had significantly higher yield per hectare and income per hectare by differences of 253.17 kg/ha and US$133.08/ha, respectively. The table shows that the average income per hectare for the whole sample is US$307.5/ha. The income per hectare are computed as the difference between the gross income from marketable yield (sales) after accounting for household consumption and the total costs of buying inputs (seed, fertilizers, chemicals), land preparation, weeding and harvesting. The opportunity cost of labor was adopted on the basis of the farm wage rates paid by farmers in the study area and the same approach was utilized for transport costs to and from the markets. The smallholder farmers have on average 4.3 ha of arable land which is characteristic of most farmers in the similar contexts in southern Africa.

A perception based measurement of soil fertility was adopted given that Tambo and Mockshell (2018), during a conservation agriculture study, reports the accuracy of farmers' characterization of the soils in their areas. The proportion of fertile soil was computed relative to the total arable land for the household and categorized as not fertile (0) and fertile (1). The variable was significantly higher for adopters (49%) as opposed to non-adopters (3%). The same was done for the availability of storage facilities at the farm which was also coded as, inadequate (0) and adequate (1) with response rates of 49.2 and 50%, respectively. This was important so as to get insights on the possible motivation to adopt the emerging CSA technology based on the potential of the soils and storage to generate income. The hypothesis was that farmers with more fertile land and storage facilities are more likely to adopt the emerging technology.

The dependency ratio had an average 35% and 33% for adopters and non-adopters, respectively. This variable was computed as the ratio of household members in the below 14 and above 65 years category relative to active household members in the 15–64 years range. Higher dependency ratios are usually an indicator of the need to adopt technologies and produce more to feed the dependents. For households with schooling, the total number of completed years in school was used to represent the education variable. Bahta et al. (2020) alluded to this when they noted that family composition has a direct bearing on technical efficiency gains as driven by sustainable agricultural management practices. The results in **Table 2** also show that the average duration in schooling of the respondents was 8 years and this was not significantly different across the adoption status. This reinforces observations by Bahta et al. (2018) who also noted homogeneity in the level of education among households in a home garden study in South Africa.

There were significantly more males in the non-adoption regime as was shown by the 15.2% difference relative to the female counterparts. Bahta et al. (2019) also noted a similar result when they recommended the need for women empowerment in as a strategy to reduce food insecurity. They argued that,

[4]Two instrumental variables, soil fertility and storage were selected as guided by the socio-economic-institutional arrangements in the study area and applied across all the outcome models.

[5]A detailed explanation of the method is found in (Ali and Abdulai, 2010; Becerril and Abdulai, 2010; Amare et al., 2012). The Kernel Method has also been widely used in literature but was not adopted in the current study.

TABLE 2 | Description of variables included in the models and descriptive statistics.

Variable	Description	Unit of measurement	Total sample mean	Adopters mean	Non-adopters mean	Difference-test
Dependent						
Productivity	A continuous variable of sorghum produced per hectare during the season	kg/ha	902.726	944.344	691.167	−2.326**
Income	A continuous variable showing income per hectare of sorghum	US$	307.452	329.328	196.250	−2.973*
Independent						
Age	Continuous variable for age of household head	Years	44.721	45.713	44.252	−0.916
Arable land	Continuous variable for the total arable land for the household	Hectare	4.3153	4.1869	4.3759	1.478
Log costs	Continuous variable of logarithm of variable costs per hectare	US$	3.859	3.829	4.009	2.517***
Dependency	Continuous variable showing proportion of household dependent members	Percent	33.258	34.738	32.558	−1.083
Education	Continuous variable of the duration in schooling by the household head	Years	8.226	7.852	8.4031	1.253
Draft	Continuous variable shoeing number of effective draft animals available	Number	5.989	6.131	5.922	−0.5796
Experience	Continuous variable of cumulative experience years in sorghum production	Years	7.679	8.909	7.097	−2.078**
Aid value	Continuous variable for the value of sorghum aid received during the season	US$	8.597	14.795	5.667	−4.383*
Associations	Continuous variable for number of social groupings for household members	Number	1.697	1.574	1.756	1.441
Distance	Continuous variable for distance to the market in kilometers	Minutes	73.647	73.525	73.705	0.019
Payment time	Continuous variable of time between finalizing a transaction and payment	Days	11.297	11.639	11.136	−0.220
Gender	Dummy variable for gender of household head (0=female, 1=male)	Dummy	0.718	0.615	0.767	2.345**
Instrumental						
Soil fertility	Dummy variable for perceived soil fertility (0=not fertile, 1=fertile)	Dummy	0.4947	0.4868	0.2872	−2.279**
Storage	Dummy variable of storage facilities adequacy (0=inadequate, 1=adequate)	Dummy	0.4955	0.500	0.492	−0.236

Source: Authors' own computation.
*; ** and *** indicate p-values significant at 1, 5, and 10% levels, respectively; t-test was used for continuous variables and chi-square for categorical variable.

this could be effectively achieved when policy interventions take center stage. A similar approach can be adopted to support gender inclusive CSA adoption pathways. **Table 2** also highlights that there were no differences in the level of farming experiences but differences in the sorghum production experiences for the adopting and non-adopting farming households in the study area. However, similar studies show the likelihood of adopters to have more experience in both the general agricultural practices and specifically sorghum production. The diversity of livelihood sources has a bearing on how the decision to adopt emerging technologies will be made. In the study, the adopters had significantly higher income diversity and crop diversity as shown by the indices computed for the two clusters in **Table 2**.

Results also show that the adopters of the blended seed-fertilizer technology fetch higher prices (US$40.13) in the markets relative to the non-adopting counterparts (US$33.61). The variability in the prices can be attributed to the pricing adopted by buyers who highly grade the produce from adopters based on a preconceived perception that they produce higher quality grain. Some of the buyers are also contracted to processors who are willing to pay higher prices for the organically produced sorghum grain. In the same way, they also interact with more buyers (∼4.0) in the markets as opposed to the non-adopting farmers (∼3.0). This can be explained by the motivation to search for buyers in more rewarding markets for the higher outputs produced at the farms. These wider interactions also create awareness among the producers on the prevailing market prices, thus enhances their negotiating leverage. And with no immediate alternative for the preferred organically produced grain, the buyers end up offering higher prices in the markets. The finding supports findings by Bahta and Enoch (2019) who also reported a similar pattern in a study which recommended the use of policy interventions among vegetable farmers in South Africa. The results in **Table 2** also show no differences in

TABLE 3 | Full information maximum likelihood estimates of productivity and income.

	Blended CSA adoption	Yield/ha		Blended CSA adoption	Income/ha	
		Adopters	Non-adopters		Adopters	Non-adopters
Variable	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
Arable land	1.046* (0.608)	2.150*** (0.749)	−3.411 (2.196)	0.014* (0.004)	0.35* (0.019)	−0.49* (0.023)
Log costs	−0.03* (0.008)	−0.242***(0.037)	0.193*** (0.0345)	−2.080* (0.677)	−0.248* (0.131)	0.057 (0.064)
Age	0.02 (0.012)	−0.67 (3.061)	−0.150 (0.1049)	−0.031 (0.013)	0.07 (0.617)	−0.177 (0.107)
Dependency	−0.01 (0.007)	−0.98 (2.001)	−0.221** (0.091)	0.022*** (0.008)	0.52 (0.405)	0.96 (0.779)
Education	−0.06 (0.046)	0.107* (0.049)	−0.322 (0.225)	−0.054 (0.047)	−0.876** (0.279)	−2.74 (3.683)
Draft	0.13** (0.059)	0.347 (0.273)	−0.034*** (0.010)	0.123*** (0.064)	1.24 (2.656)	−0.363* (0.098)
Gender	−0.41 (0.346)	−0.726 (0.503)	0.033 (0.048)	−0.642 (0.399)	−0.474 (0.321)	−0.2714 (0.2501)
Experience	−0.69 (0.279)	2.291*** (0.3632)	−0.225 (0.243)	0.332*** (0.089)	−0.158 (0.104)	0.17 (0.980)
Aid value	0.01 (0.008)	−1.876** (0.648)	−1.38** (6.552)	0.031 (0.008)	−0.934** (0.281)	0.65 (0.754)
Associations	0.24*** (0.140)	0.156** (0.064)	−0.037 (0.0319)	−0.423* (0.161)	−0.145 (0.106)	−0.555** (0.208)
Distance	0.03 (0.004)	0.51 (0.549)	−3.52 (3.268)	0.014*** (0.006)	0.246** (0.111)	1.12* (0.367)
Payment time	−0.555** (0.124)	−1.12 (2.508)	−3.212** (1.004)	−0.013 (0.020)	−0.19 (0.509)	3.31** (1.395)
Soil fertility	−1.40** (0.585)			−1.151** (0.339)		
Storage	−0.699** (0.279)			−1.194*** (0.349)		
Constant	6.69** (2.750)	−0.717*** (0.278)	−1.153*** (0.327)	0.992*** (0.3434)	4.69*** (0.4745)	2.56*** (0.4352)
rho0	−0.514 (0.1566)			−0.552 (0.1680)		
rho1	−0.1654 (0.2181)			− 0.187 (0.2736)		
/lns0	0.135*** (0.044)			3.744*** (0.2098)		
/lns1	0.593*** (0.064)			4.461*** (0.0828)		
/r0	0.568** (0.213)			0.979** (0.4481)		
/r1	0.167 (0.224)			0.349 (0.7052)		
Wald chi2 (12)	69.26***			64.23***		
Log likelihood	−495.711			−514.601		
LR test of indep. Eqns.	9.12**			7.16**		
No. of obs.	380			380		

Source: Authors' own computation.

; ** and * indicate p-values significant at 1, 5, and 10% levels, respectively; z-values estimated on robust standard errors in parenthesis.*

variables such as payment time, which shows the time between a transaction and the point of payment, the distance to the markets and the associations. In as much as there are some indicators of differences across variables, this cannot be objectively used in decision making since these are isolated summaries. Modeling the impact of the adoption decision using ESR can therefore be useful in informing the decisions while guided by the empirical evidence from the mid-Zambezi valley of Zimbabwe.

Empirical Results

The empirical analyses were done using STATA 15 statistical package where the adoption and outcome (yield/ha and income/ha) equations are jointly estimated using full information maximum likelihood approach. **Table 3**[6] shows results of the ESR with the selection equation and the equations for the two regimes (Equations 3, 4) as explained in earlier sections. The selection equation is shown in the first columns and results are explained as the normal probit model. We included the categorized percentage of fertile land available for the farmer (soil fertility) and adequacy of storage facilities as valid instrumental variables in the selection equation to assure identification (Lee, 1982; Ngeno, 2017).

The instruments, while they are uncorrelated with the two dependant variables (selected outcome indicators of income/ha and yield/ha), they are also highly significant ($p < 0.01$) in both selection models and hence we conclude that they are valid. A strong negative co-relationship with the adoption decision shows that farmers who have higher proportions of fertile land are less likely to adopt the CSA practice of using emerging varieties and inorganic fertilizers. This may be because there is more competition for fertile land with other major crops such as maize which is highly supported by the government and its agents (Sinyolo, 2020). Farmers with adequate storage facilities are also more likely to adopt the technology in anticipation of incurring less post-harvest losses after generating higher yields. This offers opportunities for tapping into market windows during the lean season phases and

[6]The variables, sigma, /lns1, lns2, /r1, and /r2, are ancillary parameters used in the MLE procedure. Sigma1 and Sigma 2 are the square roots of the variances of the residuals of the regression part of the model and lnsig is its log. r1 and r2 are the transformation of the correlation between the errors from the two equations (Lokshin and Sajaia, 2004).

fetch higher prices since commodities will be in shortage and prices more favorable.

Based on the selection criterion shown in the first column of **Table 3**, the most important factors affecting the adoption of the blended seed-organic fertilizer technology as a CSA strategy at the household level are arable land, variable costs, dependency ratio, education, availability of draft power, experience in sorghum production, value of aid, associations, distance to the market, payment time. The availability of more arable land has the propensity to significantly ($p < 0.1$). This can be explained by the patterns where the available land facilitates access to space to try out new technologies without compromising the farmer's land allocation plan, thus reducing the exposure to possible failure of the technology. Bale et al. (2013) concurs with this viewpoint and noted that, reduction in risks of crop failure is also another benefit which emanates from the availability of land where diversity in crop production helps to spread the risk tendencies. This is a fundamental outcome since there is scope for land reallocation among smallholder farmers toward the intensive producers from a policy perspective to target the production of sorghum, especially given the nature of land rights in these communities.

Associations to which household members belong has a positive bearing on the CSA adoption decision as shown in **Table 3**. This is because of the ability of networking arrangements to take place and information on the costs and benefits of these technologies discussed. The result support findings by Mutenje et al. (2016), Mapfumo (2017), and Baiyegunhi et al. (2022) who alluded that associations are hubs of information which may be critical in exposing farmers to new production systems and viable markets thereby catalyzing adoption prospects. Nciizah et al. (2021) showed that understanding this can facilitate the design of climate change adaptation strategies in the drylands of Zimbabwe. The results also show that availability of effective draft power has a positive and significant effect on the adoption decision. As such, rational farmers who have access to reliable draft power are more likely to adopt emerging productivity enhancing technologies. The variable assures timely land preparation which also plays an integral role in enhancing the performance of agricultural activities especially in the drylands where rainfall unpredictability is higher. In conservation agriculture studies by Nyanga (2012) and Abdulai (2016), similar observations were made where the multi-purpose uses of draft power in rural farming communities of southern Africa, such as for transporting inputs from markets and produce to the markets also played a part in the adoption decision. Tapping into this variable from a policy angle, as alluded to by Smale et al. (2018) can be done through livestock revolving schemes in the drylands with the aim of boosting the livestock herd and grease the production of sorghum.

In the selection model, as the variable costs increase, the likelihood of adopting emerging CSA technologies are observed to decline. This may be because, farmers who experience higher variable costs of production tend to shun these emerging technologies and possibly opt for alternative practices which are more cost effective. This is particularly so since variable costs will increase as the scale of production increases, thus crowding out prospects of adoption as driven by additional increases in land allocated toward the crop will also pull with it the variable costs structure and reduce the margins. This finding corroborates the study by Martey et al. (2021) who reported that, in farming systems, production costs are also directly related to the net benefits and need to be managed at both the operational and policy levels Makindara et al. (2013) weighs in and suggest that market mechanisms need to be readjusted to accommodate these peripheral crops if high value chains such as the clear beer chain are to generate value for stakeholders. These are critical insights into how the reduction of production costs can drive income levels up.

The dependency ratio has a positive and significant effect on the decision to adopt the blended CSA practice by the farmer. Households with larger dependency bases are more likely to be willing to experiment with emerging technologies with the hoping of getting higher yields for food and income needs. This is consistent with the findings and reasons of Ng'ombe et al. (2017) who reported the higher incidences on families with dependent members being more involved in conservation farming and getting higher revenues in the process. This isolates the need for oriented policies which aim to cushion the farmers with larger dependency ratios through for example proportional explicit subsidies. Payment time is reported to have a negative and significant effect on the farmer's proclivity to adopt the blended CSA technology. If the target crops' marketing arrangements are open to delayed payments in existing markets, then farmers will not be motivated to adopt the technology regardless of the other benefits such as yield and income gains. This is supported by Suresh et al. (2021) when they observed that some climate change adaptation strategies were less adopted because the output from their systems had challenges with payment arrangements for supply delivered to the markets. Thus, should motivate strategies which target price efficiency in agricultural market through moral suasion of legal proclamations.

The results for the two regime equations of adoption and non-adoption are shown in the second and third columns of **Table 3**. Variable costs emerge as a highly important determinant in both regimes for the yield per hectare cultivated. The same can be said for the arable land variable in relation to income per hectare cultivated. However, the income effect is relatively higher (0.49) for non-adopters as compared to the adopters (0.35). Sinyolo (2020) postulates that, as a way of looking into the future, this might act as a disincentive for the present non-adopters to migrate into the adoption cluster as they will lose a net benefit in the process. However, the variable cost structure shows that as the variable increases, then the income for the non-adopters decrease at a steeper rate relative to the yield gains. As such, assuming favorable output market prices, as currently offered by the government as an additional support package, the net effect based decision from yield and variable cost will be for farmers to adopt the emerging CSA technologies.

The results also show that for the two regimes, under income per hectare, the distance to the markets, value of aid, experience

TABLE 4 | Average treatment effect of adoption on productivity and household income.

Index	Productivity (kg/ha)			Income ($/ha)		
	Estimate	AI Robust Std. Err.	z value	Estimate	AI Robust Std. Err.	z value
ATT	243.598	124.081	1.80*	99.893	55.499	1.96**
ATU	−232.125	108.5782	2.14**	−58.958	28.663	2.06**
ATE	241.712	121.525	1.99**	93.164	50.455	1.85*

Source: Authors' own computations.
** and ** indicate p-values significant at 1 and 5% levels, respectively.*

and education are important determinants. As opposed to aprior expectations, when the distance to the market increases, the income also increases. This can be attributed to the observations from the study area which showed that distant markets are the ones which offer higher prices. As such the observed model outcome is in tandem with these observations while defying the existing hypothesis of a negative relationship between distance to the markets and income. Evidence from similar previous studies also report patterns in which experience with local markets show that they are not as lucrative as external markets (e.g., Martey et al., 2021). Decentralization of these markets can help to reduce the distance between buyers and sellers. Alternatively, the sorghum value chain actors may also invest in digital marketing alternatives. Thus, reaching out to a wider range of clients. The value of aid is also reported as an important factor when outcomes about possible gains in yield and income are made. Access to aid packages will reduce the burden of searching for and accessing inputs, thus reduces the transaction costs (Maina et al., 2015). These costs are reported by Hamukwala et al. (2010) need to be managed even from external to the farmer's plot so as to boast productivity and income.

The payment time is a significant consideration for non-adopters in both the productivity and income clusters. However, the direction of effect for the two regimes is different, and it is positive in the former and negative in the latter outcome. The variable is however insignificant in the adopters' decisions in contrast to findings by Suresh et al. (2021) who reported higher income for farmers who were paid at a later stage. This can be attributed to the likelihood that, the payment time as well as the modes used are not considerably different among the respondents in these clusters.

The treatment effects estimates for the adoption of blended seed-fertilizer technology on productivity and household income are reported in **Table 4**.

The Average Treatment Effect on the Treated (ATT) is a measure of the difference between the productivity and household income of the adopting units and the values, they had not adopted the blended CSA. Results of the ATT shows that the productivity for the treated group of farmers is positive (243.598) and statistically significant. The same can be said for the household income which is positive (99.893) and statistically significant. This implies that, the blended CSA adopting households would have been worse off in terms of income and productivity had they decided not to adopt the blended CSA package. The adoption effect of the technology on farmer's income/ha and yield/ha is approximately a 30.3 and 25.8% increase, respectively. Similarly, results from **Table 4** show that, using the Average Treatment Effect (ATE) outcomes, as derived from ESR, the non-adopting households would have attained income and productivity gains had they adopted the blended CSA technologies. The Average Treatment Effect on the Untreated (ATU), measures the difference between the productivity and household income of the non-adopters and the associated counterfactuals. The estimates account for the selection bias, in contrast to the mean differences reported in **Table 2**. Results show that, the ATU is negative for both productivity and household income with values of −232.12 and −58.96, respectively. These findings reveal that adopters of the blended CSA package would have been worse off, in both productivity and income terms, had they opted not to adopt the package, while the non-adopters would have also benefited if they had opted for the adoption pathway.

The findings, as highlighted in **Table 4** show that, the adoption of blended improved sorghum seed and partial-organic fertilizer CSA technology has a significant effect on both the productivity and household income of the adopting households. This result concurs with other studies, which also reported the gains from adoption of the different dimensions of CSA adoption (Musara and Musemwa, 2020; Mujeyi et al., 2021). As reported by Ghimire and Huang (2015) in Nepal, farmers who adopted improved maize varieties generated household wealth as opposed to the non-adopting counterparts. A study by Mujeyi et al. (2021) on the impact of CSA on household welfare in smallholder integrated crop–livestock farming systems also confirmed a robust relationship between food security, income and CSA adoption. It therefore shows that, the CSA interventions implemented in the smallholder farming societies have the potential to support gains among the adopting households in various dimensions including productivity and income. Assuming that the income/ha and yield/ha are the core desired objective for the farmers, then adopting the blended improved sorghum seed and partial-organic fertilizer package technology will be more valuable as they are likely to gain from the adoption as compared to the state of non-adoption.

CONCLUSIONS AND IMPLICATIONS FOR POLICY

The study aim was to examine the impact of adopting farmer initiated emerging CSA practices in the form of a blended improved sorghum seed variety and partial-organic fertilizer pack on productivity and net income among smallholder households in the drylands of Zimbabwe. Based on results from an ESR model, it can be concluded that, a combination of farm specific factors (arable land, variable costs) and external factors (distance to the market, value of aid) have a bearing on the adoption decision and the associated impact on productivity and income for the reviewed technology. This intricate matrix of determinants shows the crosscutting nature of these driving factors and as such the associated complexity of managing technologies through the adoption and impact management lens. Based on the average treatment analysis, it can also be reported that farmers who decide to adopt the CSA pack are relatively better off in terms of productivity and income and thus offering an incentive for adoption beyond the current coverage. In light of the conclusions, the starting point of intervention should center on multi-dimensional infrastructural development initiatives such as seed banks, information hubs and storage facilities which unlock the avenues for smallholder farmers in marginalized drylands to interact efficiently and effectively with link-agents of emerging technologies. The results could be more generalizable if study focused on a national level scale of the analysis while using a multinomial ESR for analysis. To support this, additional research can also be done on the human capital development options and how they affect the Indigenous Technical Knowledge (ITK) based entrepreneurial capabilities of the smallholder farmers in the framework of scaling out the technology.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Bindura University of Science Education Research and Ethics Committee. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

JMu and LM designed the research protocols. JMu provided the data. YB, JMu, and JMa analyzed the data and prepared the manuscript with contributions from all co-authors. YB, JMa, and LM proofread the manuscript and made suggestions for corrections. All authors read and approved the final manuscript.

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Bacterial bioinoculants adapted for sustainable plant health and soil fertility enhancement in Namibia

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The increase in dryland agriculture elicits the need to develop sustainable practices that improve crop yield and protect soil fertility. The use of biofertilisers adapted to nutrient deficient soils and arid climates would help achieve this. In this review, the use of plant growth-promoting bacteria is explored as a possible solution to the current state of dryland agriculture and climate change threats to agriculture. Plant microbe interactions form the basis of this review as evidence has shown that these interactions often exist to improve the health of plants. This is achieved by the production of important biochemicals and enzymes like indole acetic acid and amino cyclopropane-1-carboxylate deaminase while also actively protecting plants from pathogens including fungal pathogens. Research, therefore, has shown that these plant-growth promoting bacteria may be exploited and developed into biofertilisers. These biofertilisers are both economically and environmentally sustainable while improving soil quality and crop yield. The literature presented in this review is in context of the Namibian climate and soil profiles.

KEYWORDS

arid adaption, bioinoculants, legumes, plant growth-promoting bacteria, sustainable agriculture

Introduction

The state of food security today is an important factor given the challenges being faced by the agriculture sector across the whole world. These challenges include climate change (Cowie et al., 2011), droughts (Ibrahim et al., 2015), human conflicts (Ezemenaka and Ekumaoko, 2018) and an increase in land degradation (Prăvălie et al., 2019). Africa is vulnerable to food insecurity as more than 50% of its land mass is considered dryland (Prăvălie, 2016). Drylands, therefore, refer to regions that receive low amounts of rainfall and have limited arable land such as the horn of Africa (Prăvălie et al., 2019) and central Asia (Vicente-Serrano et al., 2015). Such drylands are characterized by abiotic stress such as water and nutrient deficiency, high and low temperatures, high salinity, and

UV radiation that have a significant impact on soil fertility and consequently impose an obvious limitation on crop production which in turn affect food security (Middleton and Sternberg, 2013). Therefore, there is a need to engage economic and environmentally sustainable skills, practices and knowledge systems to improve agricultural productivity in these regions, particularly in Africa (Chimwamurombe and Mataranyika, 2021).

The use of practical knowledge systems includes the expansion of the food base. This is important in regions that also incur the burden of malnutrition as a consequence of food insecurity (Chimwamurombe et al., 2020). Nutrient-dense drought tolerant crops would adequately mitigate these challenges of food security in dryland areas. Legumes offer a prime example of such crops that offer great benefits as nutritional alternatives. Some legumes of note are chickpeas (*Cicer arietinum L.*), soy beans (*Glycine max*), and marama bean [*Tylosema esculentum* (Burchell) Schreiber] (Caprioli et al., 2016; Bahroun et al., 2018; Cullis et al., 2018). Furthermore, research has observed improvement in biological soil quality after the cultivation of legumes making a strong argument for including them in crop rotations (Yu et al., 2014).

With these facts in mind, it is imperative to explore the plant microbe interactions that exist between legumes and the respective microbes. Studies have identified positive plant microbe interactions in arid climate-adapted legumes that make a compelling argument for further exploration and analysis (Bhattacharyya and Jha, 2012; Bahroun et al., 2018; Bakhtiyarifar et al., 2021). All the organisms occurring in these extreme environments, including bacteria, fungi and protozoa, develop intricate survival mechanisms to mitigate abiotic stresses (Khan, et al., 2020a). They possess the ability to express and regulate only those genes necessary to adequately adapt to the physical and chemical composition of these habitats (Martínez-Hidalgo and Hirsch, 2017). Hence, exploiting the plant-microbe interactions to sustainably meet agricultural demands in these regions is important (Verma et al., 2010; Lawless et al., 2018).

Some legumes have developed the ability to successfully grow in arid climates. These legumes offer ideal sources to isolate plant growth-promoting bacteria adapted to these climates (Dudeja et al., 2012). Common legumes grown in the arid parts of southern Africa include *Tylosema esculentum* (Chimwamurombe et al., 2016) and *Glycine max* (Igiehon and Babalola, 2018). Other legumes of note include *Lablab purpureus*, *Vigna unguiculata*, and *Macrotyloma uniflorum* (Bhardwaj et al., 2016; Grönemeyer et al., 2016; Pranesh and Ramesh, 2019). Bacterial species isolated from these legumes are also equally important due to their ability to fix nitrogen and promote growth in different stress situations. Species associated with this include *Bradyrhizobium diazoefficiens, Rhizobium etli*, *Sinorhizobium* spp. (Lawless et al., 2018) and *Mesorhizobium* spp. (Verma et al., 2010).

Namibia is a country located in the southwestern region of Africa (Ahmadalipour et al., 2019). Much of the country experiences a semi-arid to an arid climate. This is perpetuated by the low rainfall all year round and high evapotranspiration rates (Muhoko et al., 2020). Average rainfall ranges from $<$25 mm in the desert regions to 700 mm in the north-eastern regions (Montle and Teweldemedhin, 2014). Subsequently, groundwater becomes the largest source of water across the country making (Kalola et al., 2020). Namibia is also inclined to extreme climate change vulnerability (Montle and Teweldemedhin, 2014).

This review will explore known beneficial plant microbe associations in arid and nutrient poor conditions. It will focus on these interactions with Namibia in mind. It will explore interactions between legumes and microbes due to their known arid climate tolerance. Some legumes to be considered are moth bean [*Vigna aconitifolia* (Jacq.) Marechal], mung bean [*Vigna radiata* (L.) R. Wilczek var. radiata], and cow pea (*Vigna unguiculata* L. Walp). However, other plant microbe interactions will also be referenced.

Abiotic stress effects on plants

Various forms of stress affect agricultural production across the world. These may be abiotic or biotic stresses. Abiotic stresses are defined as pressures that arise from the environment. These include drought, extreme temperatures (which include freezing), abnormal salt levels and nutrient abnormalities (Suzuki et al., 2014; Enebe and Babalola, 2018). Abiotic stresses may also influence the extent to which biotic stresses affect plants. The effects may include oxidative damage to plant cells which increases susceptibility to pathogenic infections and pests. A combination of both types increases the potential threat to crop yield (Haggag et al., 2015; Pandey et al., 2017).

Drought tolerance is an important feature of plant growth-promoting bacteria (PGPB) as it offers a means to improve crop production during long periods of drought. Plant associated microbes help plants tolerate drought by enhancing the plants' physiological defenses against drought and producing different types of beneficial biochemicals such as auxins and enzymes (Ngumbi and Kloepper, 2016). PGPB can induce drought tolerance by reducing the accumulation of ethylene which impedes root elongation and eventual plant growth. This is done by the production of amino cyclopropane-1-carboxylate (ACC) deaminase, an enzyme able to catalyse the ethylene precursor ACC (Vurukonda et al., 2016; Delshadi et al., 2017). Bacteria in the genera *Arthrobacter, Bacillus,* and *Microbacterium* actively produce ACC deaminase in plants during water stress (Fadiji et al., 2021).

By producing essential amino acids and hormones, PGPB increase the plants' defenses in cases of drought stress. *Arthrobacter* and *Bacillus* PGPB, for example, contribute to proline production increasing plant growth (Kumari et al., 2016). Some *Bacillus* species, like *B. megaterium* and *B. subtilis*, produce cytokinins which are essential in drought stress tolerance (García-fraile et al., 2015). Drought tolerance may also be induced by PGP antioxidant activity. Associated endophytes increase the concentration of antioxidants such as flavonoids in plant cells.

Furthermore, evidence has shown that plant growth-promoting rhizobacteria (PGPR) help improve root systems in the event of drought stress by inducing root elongation and increasing surface area. This improves water uptake (Ngumbi and Kloepper, 2016). *Alcaligenes faecalis, Burkholderia phytofirmans* (Ngumbi and Kloepper, 2016), and *Azospirillum brasilense* (Vurukonda et al., 2016) strains are known to facilitate root elongation in drought stress conditions. This has been similarly observed in studies of *Paenibacillus polymyxa* SK1 isolated from *Lilium lancifolium* (Khan, et al., 2020b).

The morphological effects that droughts have on plants are the main causes of the reduced productivity of crops. These effects often present as reduced germination rate and seedling growth. Stunted plant growth is also often observed with decreased leaf, root and overall plant size (Hanaka et al., 2021). Plant-water potential is a parameter measured as a reflection of water energy in plants and is negatively affected by droughts. Drought stress reduces plant water potential which affects the transport of nutrients from the soil to the leaves. Plant fresh weight and biological processes such as photosynthesis which rely on water availability and nutrient transportation are also negatively affected by water stress (Ngumbi and Kloepper, 2016). Furthermore, drought stress negatively affects the biochemical processes that function to protect the plant. This results in protein and nucleic acid degradation, and weakening of membranes (Vurukonda et al., 2016).

Diversity and factors shaping rhizospheric and plant associated bacteria

Within plant tissues, microbes exist in symbiosis with the plant without causing damage to the plant. These microbes achieve this through roots, stems and/or seeds (Reinhold-Hurek and Hurek, 2011; Suman et al., 2016). Plant microbial associations include plant growth-promoting microbiome in the rhizosphere, pathogenic microbes and opportunistic human pathogens (Iyer and Rajkumar, 2017). These associations, when not pathogenic, offer positive support to the plant and soil. These plant growth-promoting microbes are known either as rhizobia or endophytes depending on whether they colonize the rhizosphere or the inner cells of the plant. Therefore, the successful colonization by the microbes contributes to the positive growth of the plant (Verma et al., 2010).

Seed endophytic bacteria influence

Diverse endophytic microbes colonize seeds forming some of the first bacterial associations in a plant's life cycle (López et al., 2018). These microbes include both bacteria and fungi (Nair and Padmavathy, 2014; Chimwamurombe et al., 2016). Seed endophytes have been observed to contribute to seed germination and cell elongation (Verma et al., 2017; Khalaf and Raizada, 2018). In addition, they form the initial microbial association for the promotion of the overall health of plants (Khalaf and Raizada, 2016). Seed endophytes can also remain quiescent in latent seeds. This means they only become active when germination begins. Furthermore, seed endophytes may be passed through to progeny with some changes occurring in the microbiome due to pathogenic infections, environmental changes or other stresses (López et al., 2018).

Seeds endophytic bacteria contribute positively to the general health of plants. Several species and genera have been identified as plant growth-promoting endophytic bacteria. Endophytic rice seedlings analysis revealed a diverse group of bacteria including *Enterobacter asburiae*, *Pantoea dispersa* and *Pseudomonas putida*. These were found to produce auxins, solubilize phosphates and inhibit pathogenic fungi (Verma et al., 2017). Through nitrogen fixation (Verma et al., 2017), hormone production (Chimwamurombe et al., 2016; Khalaf and Raizada, 2018) and antimicrobial activity (Nair and Padmavathy, 2014), endophytes improve abiotic stress tolerance and increase germination rates (Suman et al., 2016). Furthermore, they are also able to regulate hormone concentration thereby improving plant adaptation to environmental strains (Asaf et al., 2017).

Plant growth-promoting bacteria and nodulation

Root nodules are small structures typically found on legume roots. These nodules are small ranging between 2 and 5 mm containing up to 10^9 bacterial cells (Downie, 2014). Root nodule formation is triggered by simultaneous correlations between plants and their soil environment. The release of Nod factors into the soil by rhizobia temporarily activates plant genes that code for specific hormones (Spaink, 2000; Poehlman et al., 2019). Peptide hormones, for example, together with signal receptors and low levels of nitrogen in soil induce nodule formation with close association with nitrogen fixing bacteria (Taleski et al., 2018). However, nodule formation may be negatively affected by the absence of specific strains, low quorum and failure to colonize the rhizosphere (Prasanna et al., 2017). Though root nodules are mostly colonized by nitrogen fixing rhizobia, other microorganisms may also be found present in the nodules (Martínez-Hidalgo and Hirsch, 2017).

The formation of root nodules with the eventual colonization by bacteria is not fully understood however, it is known that nitrogen fixation is a result of this process. The process of nodulation is triggered by nitrogen levels in the soil with low levels initiating hormone signaling in the form of C-terminally encoded peptides (Verma et al., 2010; Taleski et al., 2018). Nod factors are produced by the bacteria as a response to signal molecules from the plant. These chemical signals include flavonoids which trigger the activation of Nod factor regulatory genes in bacteria (Spaink, 2000). This begins the process of infection with the rhizobial bacteria attached to root hairs. Once plant cell membranes detect the Nod factors, root hair deformation follows. A process that results in the nodule structure (Downie, 2014). Microbial interactions with roots tend to be location specific. Figure 1 below illustrates the specificity of different bacteria with the root system.

Bacteria associated with root nodules include *Mesorhizobium*, *Rhizobium* and *Sinorhizobium* (Verma et al., 2010). In addition, species from the *Bacillus, Bradyrhizobium* and *Leifsonia* genera have been isolated from legume nodules in semiarid regions. *Microbacterium* endophytic isolates have also been isolated from root nodules (Nunes et al., 2018; Muresu et al., 2019). The symbioses have the advantage of promoting plant growth by increasing nitrogen uptake and assisting in disease tolerance and resistance. The bacteria may also solubilize phosphate or produce plant hormones which increase plant growth (Busby et al., 2017; Muresu et al., 2019). Plants consequently take advantage of the symbiotic relationship with bacteria present in the soil facilitating the formation of root nodules (Lawless et al., 2018).

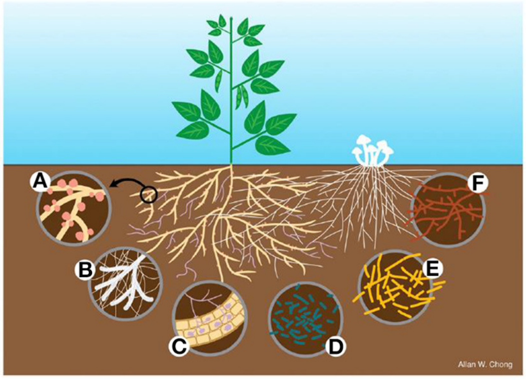

FIGURE 1
Root-nodule interactions with microbes. **(A)** Root nodules on plant roots. **(B)** Ectomycorrhizal associations with legume tree roots. **(C)** Arbuscular mycorrhizal interactions with root cells. **(D)** Gram negative rhizospheric bacteria that may influence nodule formation. **(E)** Gram positive bacteria colonize both the rhizosphere and the nodules. **(F)** Free living actinomycetes influence plant growth by nitrogen fixation among others. Adapted from Martínez-Hidalgo and Hirsch (2017).

Rhizospheric influence on plant growth promotion

The rhizosphere is described as the soil region closest to the roots. It acts as a platform for close interaction within the biosphere around the roots of plants (Jha and Saraf, 2015) and is largely influenced by the plant roots themselves (Ai et al., 2011; Semenov et al., 2020). Therefore, bacteria that colonize the rhizosphere are known as rhizobacteria (Haiyambo et al., 2015).

Through the action of root exudates and essentially chemotaxis (Figure 2) the rhizosphere is a microbe-rich zone (Orozco-Mosqueda et al., 2018; Swarnalakshmi et al., 2020). Also referred to as inter-kingdom signaling, chemotaxis forms the basis for the initial colonization of the rhizosphere by microbes (Venturi and Keel, 2016). As a result, it is a site for biological functions including microbial activity (Fernández Lópeza et al., 2013) and water regulation (Zhang et al., 2020). Both fungal and bacterial organisms form the population of microbes that occupy the rhizosphere (Bui and Franken, 2018; Liu et al., 2019; Leontidou et al., 2020; Sharma et al., 2020).

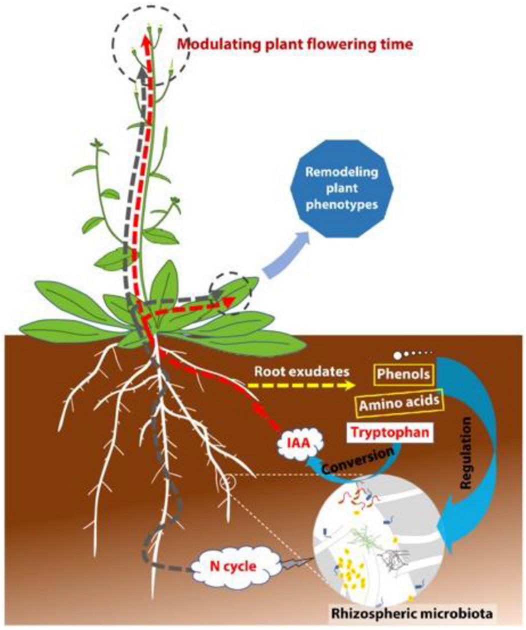

FIGURE 2
Rhizospheric interactions between the environment, microbes, and plants. Adapted from Lu et al. (2018).

Rhizobacteria possess the unique ability to influence plant systems both directly and indirectly (Enebe and Babalola, 2018). They offer positive support and influence the crops by performing or facilitating various biological processes. These include solubilisation of inorganic forms of essential compounds

(Kaushal and Kaushal, 2015; Puri et al., 2020), biological nitrogen fixation (Tamagno et al., 2018) and antimicrobial activity (Qiu et al., 2012; Martínez-Hidalgo and Hirsch, 2017) among others. The microbial community of the rhizosphere, as such, is heavily influenced by microbes present in the general soil mass (Mendes et al., 2014).

The rhizosphere forms the primary stage for the exchange of nutrients and compounds between the plants and rhizobacteria. This is made possible by carbon rich root exudates that make the rhizosphere a nutrient rich region. This favors microbial growth (Orozco-Mosqueda et al., 2018; Semenov et al., 2020). The physical characteristics of the rhizosphere also create a suitable environment to accommodate both aerobic and anaerobic bacteria among others (Jha and Saraf, 2015; Chawngthu et al., 2020).

One important role played by the rhizosphere is the contribution it makes to water uptake from the bulk soil into plant roots. The uptake of water by plants from the bulk soil is a well understood process, however, the influence of the rhizosphere is often overlooked. Through an intricate interaction between the plant and rhizosphere, the water uptake is regulated (Carminati et al., 2010). This is initiated by plant roots that have been observed to produce a gel like substance (mucilage) that is held within the rhizosphere. Mucilage modifies rhizospheric soil properties resulting in improved water storage (Zeppenfeld et al., 2017; Zhang et al., 2020). Mucilage also has an additional function of inducing hydrophobicity in the event of reduced water availability. This allows for biophysical protection of the plant from drought (Kroener et al., 2016).

In addition, research strongly suggests that rhizospheric influence may differ depending on the age of the roots. This implies, therefore, that distal (younger) roots experience a greater mucilage occurrence to improve water uptake compared to proximal (older) roots (Carminati, 2013). Therefore, the hydraulic properties of the rhizosphere together with root exudates play a crucial regulatory role in water uptake by plants.

Root exudates are nutrient rich carbon sources ideal for microbial communities. They also offer a certain degree of influence on the microbiome (Semenov et al., 2020). Due to this influence and its physical properties, the rhizosphere creates an ideal environment for microbes. With this, the rhizosphere is able to house a wide variety of microbes whose composition is often influenced by plant roots (Essel et al., 2019). Distinct differences in microbiomes between the bulk soil and rhizosphere exist, however, the multiplicity decreases around the rhizosphere (Cui et al., 2019). In addition, the rhizospheric microbiome is more functionally structured compared to the bulk soil. This strongly points toward ecological stability within the rhizosphere (Zhang et al., 2017; Tian et al., 2022).

The rhizospheres of all plants are characterized by bacteria from several different genera. These include *Bacillus, Enterobacter* and *Pseudomonas* (Haiyambo et al., 2015). Some of the most abundant bacterial genera that have been identified within the rhizosphere are *Lactococcus, Nocardioides, Pseudarthrobacter, Rhizobium* and *Streptomyces* (Essel et al., 2019). The rhizosphere of legumes also includes a similar microbial profile. Rhizobacteria isolated from the chickpea rhizosphere include *Azotobacter chroococcum, Bacillus pumilis, Bacillus subtilis* and *Pseudomonas aeruginosa* (Pandey et al., 2019). Hence, other legumes like dolichos bean (*L. purpureus*) that have formed beneficial symbioses with bacteria become ideal candidates for sustainable intercropping practices.

Use of bioinoculants in crop improvement

Bioinoculants or biofertilisers are microorganisms developed for application to the surface of plants, seeds or mixed with the soil with eventual colonization of the rhizosphere or endosphere of the plants. They promote plant growth and improve nutrient use and uptake by the plant (Singh, 2013). The identification of PGPB and eventual growth-promoting traits has led to the use of bacteria strains as bioinoculants. These associations may be used in sustainable agriculture to substitute the use of chemical fertilizers.

Inoculation of soil or seeds with bioinoculants improves plant growth of plants. Root length, for example, may be influenced by inoculation of seeds with *Azospirillum brasilence* and *Pseudomonas putida* which are both known to encourage plant growth due to their ability to produce IAA (Shahab et al., 2009). Further evidence indicates plant growth improvement by the production of bioactive metabolites of PGPB isolated from the roots of *Salvia miltiorrhiza*. These contribute toward pathogen inhibition and improved disease tolerance and resistance (Duan et al., 2013). The use of bioinoculants has been assessed in Namibia on the growth of cowpea varieties. The study observed increases in yield of approximately 30% (Luchen et al., 2018).

The use of bioinoculants is further motivated by their environmental benefits. Unlike chemical fertilizers, biofertilisers do not leach into the soil and water nearby, a process known as eutrophication (Wimalawansa and Wimalawansa, 2015; Ouyang et al., 2018). However, this may be negatively affected by the chemical composition of the soil. Long-term exposure to fertilizers, for example, impacts the rhizospheric microbiome often reducing the diversity of PGP bacteria (Semenov et al., 2020).

Plant growth-promoting traits

1-aminocyclopropane-1-carboxylate (ACC) deaminase

Ethylene is a phytohormone with a regulatory role necessary for plant growth when in low concentrations. However, abiotic

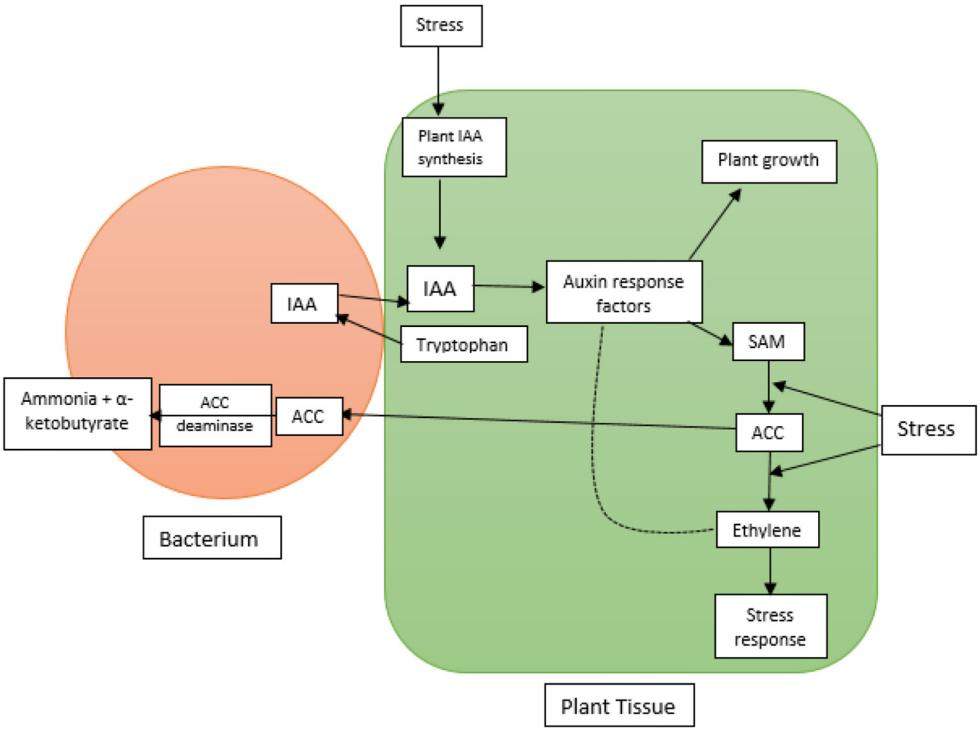

FIGURE 3
The image above [as described by Glick (2014)] shows the bacteria-assisted production of ammonia and α-ketobutyrate through the action of ACC deaminase as a response to stress on plants. Abbreviations: ACC - 1-aminocyclopropane-1-carboxylate; IAA - indole acetic acid; SAM - S-adenosyl methionine.

and biotic stresses trigger a different response (Ghosh et al., 2018). Stress events such as drought and higher temperatures induce the production of plant growth limiting compounds such as ethylene (Gupta and Pandey, 2019a). During drought stress, a frequent problem in arid and semi-arid regions, ethylene is produced as a stress signal. The increased water stress accelerates the oxidation of 1-aminocyclopropane-1-carboxylic acid from S-adenosyl methionine. A reaction that results in the production of ethylene (Danish and Zafar-Ul-Hye, 2020). An unregulated increase in "stress ethylene" results in the death of shoots and roots leading to the plant eventually failing to thrive (Singh et al., 2015). The presence of the enzyme ACC deaminase regulates the amount of ethylene in the plant. This is done by the hydrolysis of ACC to ammonium and α-ketobutyrate (Penrose and Glick, 2003). Studies have noted that ACC deaminase can effectively eliminate drought stress effects and this has been observed in pea crops (Ghosh et al., 2018).

ACC deaminase is also especially useful in increasing plant stress tolerance in events of high salinity and pathogenic infections (Bhattacharyya and Jha, 2012). Furthermore, the presence of ACC deaminase promotes nodule formation supporting plant growth. Some bacterial species produce ACC deaminase that actively breaks down ACC to ammonium and α-ketobutyrate (Belimov et al., 2001; Tsukanova, 2017). It has been noted, however, that ACC deaminase activity is higher in phosphorous deficient environments than in phosphorous abundance (Alemneh et al., 2020). Essentially ACC deaminase, by reducing the amount of ethylene, can influence an increase in root length (in the event of water stress) and improved nutrient uptake (in situations of nutrient deficiency) (Alemneh et al., 2020).

To determine the presence of ACC deaminase, bacterial isolates are tested for their ability to utilize ACC as the sole source of nitrogen (in the form of ammonium) (Penrose and Glick, 2003). This is achieved by inoculating the bacterial samples onto augmented Dworkin Foster minimal salt media with added ACC. Growth on these plates would indicate the presence of active ACC deaminase. An additional step measures the activity by determining the amount of α-ketobutyrate and ammonium produced (Ali et al., 2014). The process of the production of ammonia and α-ketobutyrate *via* ACC deaminase activity is shown in Figure 3 below. Molecular analysis of the isolates *via* 16S rRNA primers provides their identities. Some known bacteria species which are capable of hydrolyzing ACC include *Pseudomonas putida* strain Am2, *P. brassicacearum* strain Am3, *Variovorax paradoxus* strain Bm2, *P. putida* strain Bm3 (Belimov et al., 2001), *P. fluorescens* strain FPG3 (Ali et al., 2014), *Paenibacillus sp*. strain

SG_AIOA2 and *Aneurinibacillus aneurinilyticus* (Gupta and Pandey, 2019a).

Phosphate solubilization

Minerals in insoluble forms cannot be taken up and utilized by plants, hence the need for chemical fertilizers. Phosphorous is one such mineral (Khandare et al., 2020). Phosphate solubilizing bacteria convert inorganic phosphate (Pi or PO_4^{3-}) into more soluble forms (HPO_4^{2-} or H_2PO_4) that can be taken up and utilized by the plant. Bacteria achieve this by secreting acids that facilitate solubilization. Succinic acid is one such acid produced by several strains of *Bacillus megaterium* (Suleman et al., 2018; Zheng et al., 2018).

Phosphorous is an essential nutrient required for the growth and development of plants. It is a crucial element in DNA and RNA, adenosine triphosphate (ATP) and phospholipids (Daneshgar et al., 2018). Thereby positively contributing to photosynthesis, root elongation and nitrogen fixation (Matse et al., 2020). The availability of phosphorous to plants is crucial in soils with low concentrations of biologically available phosphates (Khandare et al., 2020). Furthermore, by using phosphate solubilizing PGPR in agriculture the use of environmentally damaging phosphate fertilizers is avoided. These phosphate fertilizers are known to leach heavy metals into water sources (Bhattacharyya and Jha, 2012).

To characterize bacteria for phosphate solubilization, isolates are grown on Pikovaskya's agar plates with 2% inorganic Tricalcium phosphate ($Ca_3(PO_4)_2$ (Pandey et al., 2019) or a tris-minimal medium with added zinc phosphate (Shahab et al., 2009) and monitored. A molecular technique may also be employed in the identification and characterization of phosphate solubilising bacteria. This method entails the identification of phosphate solubilising genes in bacterial isolates. Using gene specific primers, genes may be identified (Zheng et al., 2018). This, however, is an inconclusive technique as it only indicates the ability of the bacteria to solubilise phosphates but does not reveal the level of expression of the genes.

Bacteria known to solubilize inorganic phosphate include *P. fluorescens*, *P. putida, Xanthomonas maltophilia* (Gupta et al., 2014), *Enterobacter agglomerans* and *Rhizobium leguminosarum* (Bhattacharyya and Jha, 2012). Some studies have identified bacterial strains in co-inoculation studies that improve phosphorus uptake. Improved phosphorous content was observed when *Rhizobium spp* strains (CHB1120 and CHB1121) were inoculated with *Azotobacter vinelandii* (strain G31) and *Bacillus aryabhattai* (strain Sb) (Matse et al., 2020).

Siderophore production

Iron is one of the most crucial elements for plant growth and is essential for plants to maintain ion homeostasis. It is also an essential component as plants are the main source of iron for humans. Iron deficiency in plants, therefore, is a serious problem (Rai et al., 2021). Some PGPR can produce siderophores that improve the uptake of iron by plants. These siderophores, by forming chelating complexes, promote plant growth by improving the availability of iron to plants and microbes. Siderophores are low molecular weight compounds released by organisms that have a high chelating affinity for ferric iron (Dudeja and Giri, 2014). These compounds solubilise ferric iron into more soluble forms (Fe^{3+} complexes) that are more easily taken up by plant cells (Gamit and Tank, 2014).

The functions of the siderophores promote plant health. As previously mentioned, nitrogen is an essential nutrient required by all plants. For nitrogen to be fixed, bacteria require the enzyme nitrogenase which contains iron. Therefore, sufficient amounts of iron are required (Singh et al., 2018). Iron is also an essential mineral required by plants for growth and development. Using iron-chelating siderophores, PGPR improve the uptake of iron in iron-deprived soils (Dastager et al., 2011). Siderophores also play a secondary role in biocontrol. By chelating ferric iron, they reduce the availability of free living iron in the soil which is required by phytopathogenic microbes (Bhattacharyya and Jha, 2012; Majeed et al., 2015). This has been observed in the control of pathogenic fungi by reducing the availability of iron (Penrose and Glick, 2003; Goswami et al., 2014).

Ligands that chelate iron (III) are used to classify and identify siderophores, these include carboxylates, catecholates and hydroxamates (Louden et al., 2011). Chrome azurol S (CAS) agar, with a pH indicator, is often used as a universal identifier for siderophore production tests. Isolates are inoculated onto CAS agar and observed for color change. The presence of a yellow halo around inoculated isolates indicates siderophore production (Schwyn and Neilands, 1987; Batista et al., 2017). Siderophore producing rhizobacteria in the genera *Azadirachta*, *Azotobacter*, *Bacillus*, *Pseudomonas* and *Rhizobium* contribute positively to plant growth and improvement of chlorophyll content (Gamit and Tank, 2014; Gupta et al., 2015). *Pseudomonas* sp. strain GRP3 from *V. radiata* supports iron uptake because of efficient siderophore production (Glick, 2012). Some siderophore producing species include *Bradyrhizobium japonicum*, *Rhizobium leguminosarum* and *Sinorhizobium meliloti* (Bhattacharyya and Jha, 2012).

Indole-3-acetic acid production

Indole-3- acetic acid (IAA), a growth-promoting auxin, stimulates root elongation and root hair growth. It is synthesized from tryptophan (Lu et al., 2018). However, previous studies have also identified bacteria that can produce IAA without the use of a tryptophan precursor (Kumari et al., 2016). It is an essential plant growth-promoting compound that offers positive support during drought stress, nutrient deficiency, and high salinity.

Extended periods without water (drought stress) mean the amount of water available to plants decreases continuously. However, IAA creates a metabolic reaction that improves water and nutrient uptake (Etesami, 2018). IAA stimulates root elongation and increases root hairs during drought stress. Furthermore, by increasing cell-water uptake efficiency and protein synthesis, IAA promotes embial activity. This in turn promotes increased nutrient uptake, (by longer roots) and induces flowering and fruiting (by delayed abscission) (Mohite, 2013).

The presence of IAA has also been attributed to increased salt tolerance by plants. By improving and maintaining the homeostasis of auxins and phytohormones, IAA supports salt tolerance. This is of importance as high salinity affects hormone production and balance (Saleem et al., 2021). Plants infected with IAA producing PGPB have been found to contain higher levels of antioxidant enzymes which increase salt tolerance (Viscardi et al., 2016). However, salt tolerance may also be enhanced with physical modifications induced by IAA. Khalid and Aftab (2020) observed salt tolerance samples with IAA. They attributed this tolerance to a possible increased salinity tolerance threshold made possible by the improved root length and cell extension.

IAA production may be assessed from bacterial isolates and quantified using different methods. Microbial analysis of IAA production often follows the growth of isolates in Luria-Bertani (LB) broth with tryptophan and incubated while shaking. Samples will thereafter be centrifuged and supernatant extracted for quantification using a spectrophotometer (Rajendran et al., 2012). Isolates can also be grown in yeast malt dextrose broth and quantification of IAA can be done using thin layer chromatography (Mohite, 2013). Some IAA producing genera include *Azotobacter, Azospirillum, Bacillus, Kocuria, Pseudomonas*, and *Rhizobia* (Bhattacharyya and Jha, 2012; Goswami et al., 2014).

Antifungal activity

Biotic stresses are major threats to crop production and yield and often results from fungal, bacterial, or viral infections. These infections cause great losses. Sub-Saharan Africa has recorded losses of more than 220, 000 tons due to fungal infections in common beans. The result of this on a global scale is approximately 800 million people being undernourished (Burke, 2010; Rajendran et al., 2012). Therefore, the antifungal activity of biofertilisers is an important characteristic.

One important fungal pathogen to legumes is *Colletotrichum lindemuthianum*. It affects *L. purpureus* (dolichos bean) and causes anthracnose disease which often results in yield loss. *V. radiata* (mung bean) is also susceptible to anthracnose infection with losses sometimes reaching up to 60% of planted crops (Bhutani et al., 2018). Other important fungal species are in the genus *Fusarium*. These include *F. oxysporum* and *F. solani* which are common pathogens that affect legumes (Burke, 2010; Eid and Fouda, 2021). Antifungal activity of plants by endophytic bacteria, therefore, is beneficial and contributes to plant growth-promoting activities (Haiyambo et al., 2015).

The antifungal activity of endophytic bacteria may be determined by molecular analysis or microbiological techniques. Molecular analysis of bacterial endophytes with primers allows for the detection of genes for antifungal compounds. Previous studies have identified the following genes *phzC-phzD, prnD, pltc, phz, phlD* and *hcnAB* to code for the production of antifungal compounds such as phenazine, phenazine-1-carboxylic acid and pyrrolnitrin (Bahroun et al., 2018). Metagenomics may also be used to detect antifungal clones in isolates, however, this method often results in low detection (Burke, 2010).

Antifungal compounds produced by endophytic bacteria actively inhibit the growth of pathogenic fungi. Microbial analysis of antifungal activity follows the concept of the inhibitory potential of isolates (Bhattacharyya and Jha, 2012). Isolates from *V. radiata* have been found to produce hydrogen cyanide which actively inhibits pathogenic fungi (Bhutani et al., 2018). To determine antifungal activity, fungal isolates are grown on potato dextrose agar (PDA) plates co-inoculated with bacterial isolates with antifungal abilities (Rajendran et al., 2012). Zones of inhibition indicate the degree of efficacy of antifungal compounds produced.

PGPB with antifungal activity can be isolated from different plants. An endophytic bacterium (*Paenibacillus polymyxa* SK1) isolated from bulbs of the *Lilium lancifolium* was found to possess significant antifungal activity. *P. polymyxa* SK1 was shown to actively inhibit *Botrytis cinerea, Botryosphaeria dothidea, Fusarium fujikuroi* and *F. oxysporum,* all detrimental fungal pathogens (Khan, et al., 2020b). Some *Staphylococcus* strains have been found to reduce drought stress but also inhibit fungal infections in plants (Eid and Fouda, 2021). *Streptomyces murinus* is a well-studied endophyte with antifungal activity. The most significant activity has been observed against *Gibberella fujikuroi*, *Aspergillus niger* and *Aspergillus fumigatus* all-important plant pathogens (Sun et al., 2013).

Nitrogen fixation

One of the most beneficial characteristics of plant growth is nitrogen fixation. Biological nitrogen fixation (BNF) is the process of supplying available nitrogen to the plant through microbial action. This is a trait that has been observed more often in legumes. *L. purpureus* and *Cajanus cajan* (pigeon pea) are examples of such legumes (Mendonça et al., 2017). This can be facilitated by bacteria (also referred to as diazotrophs)

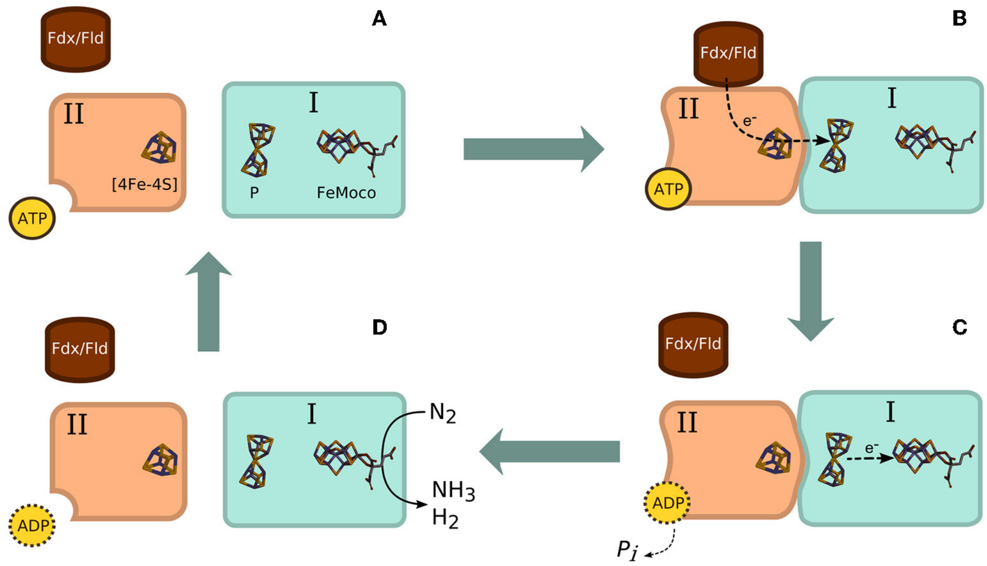

FIGURE 4
Schematic presentation of nitrogen fixation via nitrogenase facilitation. **(A)** Detached nitrogenase components I (*dinitrogenase; MoFe protein*) and II (*dinitrogen reductase; Fe protein*) show II awaiting reduction by ATP. **(B)** ATP binds to component II initiating electron transfer from donor [Fdx (*ferredoxin*) or Fld (*flavodoxin*)]. ATP binding triggers an allosteric structural change which leads to the components attaching. A flow of electrons occurs from the [4Fe-4S] cluster on II to the P cluster on I. **(C)** Electrons are further shuttled to the cofactor-iron-molybdenum cofactor (FeMoco) while ATP is hydrolysed to adenosine diphosphate (ADP). **(D)** The two components detach and produce ammonia and H_2 via the reduction catalysed by nitrogenase (Seefeldt et al., 2009). Image by R Patrícia.

that fix atmospheric nitrogen (N_2) to more biologically available ammonium form (NH_4^+). This reaction typically occurs in root nodules (Chidebe et al., 2018). This characteristic is especially crucial for plants growing in nitrogen poor soils. The chemical equation and Figure 4 below represent the process of nitrogen fixing. Studies have found that the enzyme nitrogenase catalyses the reaction below (Das and Microbial, 2018; Saiz et al., 2019).

$$N_2 + 10H^+ + 8^{e-} \rightarrow 2NH_4^+ + H_2(16\ ATP)$$

For nitrogen content, BNF plays a crucial role in improving soil fertility. In addition, it has been documented that close to 80% of all BNF occurrences are through symbiotic bacteria while non-symbiotic activity also contributes significantly (Gothwal et al., 2008; Das and Microbial, 2018). Non-symbiotic bacteria also referred to as free living nitrogen fixing (FLNF) bacteria can occur throughout the soil. However, they are often restricted to the rhizosphere due to the availability of carbon from the plant (Smercina et al., 2019).

The rate of nitrogen fixation is measured to determine the nitrogen fixing abilities of microbes. This is done in one of two ways, acetylene reduction assay (ARA) or the $^{15}N_2$ incorporation method (Smercina et al., 2019). ARA is based on the reduction activity of nitrogenase enzyme on acetylene to ethylene (Saiz et al., 2019). To assess nitrogen fixing activity, isolates are grown on nitrogen free medium with an indicator. Isolates that show growth are thereafter inoculated into nitrogen free broth. This is followed by inoculation and growth in enriched cultures in vials allowing to produce ethylene. The ethylene produced is then measured by gas chromatography (Gothwal et al., 2008; Baldani et al., 2014).

However, ARA requires the use of a conversion factor to estimate the biological nitrogen fixation rate based on the number of moles of ethylene produced. The conversion factor is often approximately 4:1 (Saiz et al., 2019). The latter method, on the other hand, is more accurate as it measures nitrogen fixation based on the differences in ^{15}N isotope abundance when exposed to $^{15}N_2$ standard samples. However, this method carries a higher risk of contamination (Smercina et al., 2019). In addition to these two methods, a microbial bioassay may also be used. In this method, isolates are grown on a nitrogen free medium before growth on Jensen's medium plates under N_2 atmosphere. Colony growth is then monitored and measured using a haemocytometer. A published equation is then used to calculate the rate of BNF (Das and Microbial, 2018).

There exists a catalog of nitrogen fixing bacteria that play an important role in plant growth promotion. Many of them have been isolated from legume species from roots, rhizosphere, and nodule endosphere. These include, among many others, *Phaseolus vulgaris, V. angularis, V. subterranea,* and *L. purpureus* (Andrews and Andrews, 2017). Within that list of bacteria are *Bacillus pumilis* and

TABLE 1 Bacterial plant growth-promoting interactions.

Trait	Effect on plant	Genus/species	Common hosts	References
Phosphate solubilization	Increases phosphate uptake by plants	*Bacillus megaterium, Enterobacter agglomerans, Enterobacter asburiae, Pantoea dispersa, Pseudomonas putida* and *Rhizobium leguminosarum*	*Raphanus raphanistrum, Vigna radiata, Oryza sativa,* and *Triticum aestivum*	Bhattacharyya and Jha, 2012; Verma et al., 2017; Suleman et al., 2018; Zheng et al., 2018
Antifungal activity	Prevents fungal pathogenic infections	*Enterobacter asburiae, Pantoea dispersa, Bacillus amyloliquefaciens, Paenibacillus polymyxa, Streptomyces murinus* and *Pseudomonas putida.*	*Polygonum cuspidatum,* and *Oryza sativa, Lilium lancifolium*	Sun et al., 2013; Shahzad et al., 2017; Verma et al., 2017; Khan, et al., 2020b
ACC deaminase production	Actively cleaves ACC (precursor to ethylene) to lessen the effects of drought and salt stress	*Pseudomonas putida, Pseudomonas brassicacearum, Variovorax paradoxus, Pseudomonas fluorescens, Paenibacillus sp.* and *Aneurinibacillus aneurinilyticus*	*Pisum sativum, Brassica juncea, Tylosema esculentum* and *Brassica juncea*	Belimov et al., 2001; Ali et al., 2014; Chimwamurombe et al., 2016; Gupta and Pandey, 2019b
IAA production	Improve cell-water uptake efficiency and protein synthesis during drought and salt stress	Bradyrhizobium sp., *Azospirillum sp.,* Enterobacter cloacae *Bacillus sp., Rhizobium leguminosarum* and *Pseudomonas*	*Triticum aestivum, Raphanus raphanistrum, Oryza sativa,* and *Suaeda fruticosa*	Bhattacharyya and Jha, 2012; Goswami et al., 2014
Siderophore production	Increases uptake of iron by plants and reduces available iron to fungal pathogens	*Staphylococcus spp., Microbacterium spp., Pseudomonas spp., Chryseobacterium spp., Burkholderia spp.,* and *Bacillus spp.*	*Paullinia cupana, Salix purpurea, Eleocharis obtuse* and, *V. radiata*	Batista et al., 2017; Olanrewaju et al., 2017; Oleńska et al., 2020
Biological nitrogen fixation	Increases nitrogen uptake especially in nutrient poor soils	*Mesorhizobium spp., Rhizobium spp. and Sinorhizobium spp., Bacillus pumilis, Rhizobium larrymoorei, Rhizobium oryzae, Rhizobium undicola* and *Bacillus subtilis*	*Phaseolus vulgaris, V. angularis, V. subterranea, T. esculentum* and *L. purpureus*	Verma et al., 2010; Kaushal and Kaushal, 2015; Chimwamurombe et al., 2016; Andrews and Andrews, 2017

B. subtilis which have been isolated from the rhizosphere of cauliflower plants. Studies found strains from both species to positively influence plant growth (Kaushal and Kaushal, 2015). *Rhizobium larrymoorei, Rhizobium oryzae* and *Rhizobium undicola* are known to fix nitrogen in association with the legume *Tylosema esculentum* locally known as marama bean (Chimwamurombe et al., 2016). Other genera identified include *Bradyrhizobium*, *Mesorhizobium*, *Ensifer* and *Azorhizobium* (Wasai and Minamisawa, 2018). Table 1 below summarizes some of the most important species and genera for plant growth-promoting bacteria.

Concluding remarks

The semi-arid to arid climate of Namibia makes it vulnerable to the increasing threat of climate change affecting the world over. This further threatens subsistence farming which rural populations rely heavily on. Therefore, the development and use of plant growth-promoting bacteria as bioinoculants favors farmers, the population, and the environment. Research on plant microbial associations of arid-adapted crops like legumes would help facilitate more environmentally sustainable practices in agriculture with the Namibian climate and soil profiles in mind. We recommendation that work be put into developing plant growth-promoting bacteria associated with legumes that are currently grown in Namibia into bioinoculants for use in Namibia and other dryland regions across the globe. Furthermore, it is also recommended that subsistence farmers be included in developmental stages as crucial stakeholders of the developed bioinoculants.

Author contributions

PM: conceptualization and writing–original draft. PC, VV, and JU: writing–review and editing and supervision. 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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Management practices and rice grain yield of farmers after participation in a joint experimentation

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Low productivity of rice in Uganda is attributed to sub-optimal production practices related to soil nutrient, crop and weed management. Application of improved management practices could enhance productivity. Returning 1 year after a joint experimentation in which different components of recommended agronomic practices (RAP) for rice were tested, we assessed change in management practices and grain yield of participating farmers (participated in joint experimentation) and non-participating farmers (did not participate) with plots in the same irrigation scheme. Participating farmers belonging to the lower-yielding farmers under farmers' practice (FP) during joint experimentation improved their management practices, compared with the middle- and top-yielding farmers. Sixty-one, 24 and 7% of lower-, middle- and top-yielding farmers, respectively, weeded earlier after experimentation compared with weeding time under FP during joint experimentation. Seventy-nine percent of lower-yielding farmers used fertiliser after experimentation compared with 18% during experimentation, with a higher N rate increase than middle- and top-yielding farmers. Overall, participating farmers transplanted and weeded earlier, and applied slightly higher N rates compared with non-participating farmers. Top-yielding farmers had significantly ($p = 0.03$) higher grain yield, followed by middle- and lower-yielding farmers. However, lower-yielding farmers made significantly ($p < 0.001$) higher yield gain than middle- and top-yielding farmers. A paired *t*-test showed that average yield gain was 1,358 (1,027–1,689), 473 (252–695) and −91.7 (−397–213) kg ha^{-1}, respectively, for lower-, middle- and top-yielding farmers. Participating farmers had higher grain yield (4,125 kg ha^{-1}) than non-participating farmers (3,893 kg ha^{-1}). Three farm types were identified that differed in application of RAP, however, with small differences in household characteristics. The farm type with higher fertiliser use in nursery and field, line transplanting, timely weeding and higher N rate had the highest grain yield. We conclude that joint experimentation had a larger effect on raising yield of lower-yielding farmers, bringing farmers closer in their management and outputs. Lack of differences among farm households could indicate that wealth is not crucial in innovation adoption in this production system.

KEYWORDS

joint experimentation, participating farmers, non-participating farmers, recommended agronomic practices, *Oryza sativa*

Introduction

Rice (*Oryza sativa* L.) in Uganda has become an important food staple and cash crop, especially among smallholder farmers, making it the second most important cereal after maize [KilimoTrust, 2014; Uganda Bureau of Statistics (UBOS), 2021]. Yet, rice yield in Uganda averages only 2,800 kg ha^{-1} for both irrigated and rainfed rice compared with the global average yield of 4,700 kg ha^{-1} [Food and Agriculture Organisation of the United Nations (FAO), 2021], and a yield potential in sub-Saharan Africa of 9,200 and 7,000 kg ha^{-1} for irrigated and rainfed rice, respectively (Global Yield Gap Atlas, 2022). As a result, demand for rice surpasses production, which has resulted in an average net annual milled rice import of around 62,000 tonnes between 2015 and 2020, costing the country about USD 23.2 million each year [Food and Agriculture Organisation of the United Nations (FAO), 2022]. The low yield is attributed to, among other factors, soil-related constraints, poor management of rice fields, and use of low-yielding varieties.

Application of modern agricultural production technologies, such as improved weed management practices, appropriate use of inorganic fertilisers, and modern, high-yielding varieties could enhance rice crop productivity, hence reducing shortage and saving money spent on imports. This is in addition to increasing household food security, reducing poverty directly through increased household incomes and welfare, and indirectly through lower food prices and higher wages (Kassie et al., 2011, 2018; Manda et al., 2019; Wossen et al., 2019). Yet, even with the evident benefits of many of the new agricultural technologies, smallholder farmers either do not adopt them or it takes a long time for such technologies to start being adopted (Mottaleb, 2018). The lack of or slow adoption of improved agricultural technologies is attributed to high costs, uncertainties about proper application and success under local farmers' environmental conditions, and farmers' perceptions and expectations (Mottaleb, 2018; Sinyolo, 2020). Further studies show that variation in adoption of improved management practices that enhance crop yields is related to differences in socio-economic characteristics of farm households, including, for instance, family size, farm size and income, farmers' age and education, labour availability, availability of cash for investment, and risk perception (Danlami et al., 2016; Fosso and Nanfosso, 2016; Hassan et al., 2016; Tadesse et al., 2017; Takahashi et al., 2020; Urfels et al., 2021). Moreover, past participation in on-farm trials, training and awareness about the technology, and contact with extension agents are shown to influence adoption (Danlami et al., 2016, 2019; Hassan et al., 2016; Takahashi et al., 2020). Due to such constraints, improved agricultural technologies may not necessarily result in poverty reduction as some of these constraints make improved technologies inaccessible and less profitable for the poorer farmers (Wossen et al., 2019).

Increasing rice production for enhanced food and income security requires understanding the intricacy of smallholder rice farms in Uganda and their use of improved management practices (Giller et al., 2011; Priegnitz et al., 2019). Getting insights into the diverse and specific farm types necessitates evaluating the uptake of improved management practices in the rice production system together with the socio-economic characteristics and the associated variation in yield among rice farmers. Developing farm typologies i.e., collections of farms that are homogeneous in uptake of improved management practices (Priegnitz et al., 2019) is thus the first and crucial step in examining the adoption of improved management practices in smallholder farms. These typologies could help support more strong policy interventions as well as advisory programmes to improve the adoption of production technologies to increase rice yields (Banerjee et al., 2014). Typologies can also be used to help support the development, implementation and monitoring of agricultural development projects; and to develop more suitable agricultural technologies and policies for less-favoured regions and households. This is in addition to being a practical framework for designing differentiated approaches to addressing rural challenges (Kuivanen et al., 2016; Priegnitz et al., 2019).

This study assessed the change in management practices and grain yield of rice farmers 1 year after the end of a 1-year joint experimentation, conducted between January and December 2019 on-farm together with farmers, where different components of recommended agronomic practices (RAP) for lowland rice production were tested (Awio et al., 2022). Farm types were identified and characterised based on packages of RAP applied on-farm. Components of RAP that were used to form clusters of farms based on how these improved management practices were taken up by the farmers included field levelling, use of certified seed, use of fertiliser in the nursery bed, timely transplanting, line transplanting, gap-filling, use of fertiliser in the field, and timely weeding. For these farm clusters, differences in their socio-economic characteristics and additional rice farming practices were evaluated. The overall objective of the study was to evaluate how the joint experimentation with farmers translated 1 year later in changes in farmers' management practices and, hence, grain yield, and to identify factors that were related to uptake of improved management practices. Specific objectives of the study were (i) to assess change in management practices and the related change in grain yield of farmers 1 year after participation in joint experimentation, (ii) to compare management practices, grain yield and yield gap of farmers who participated and those who did not participate in the joint experimentation, and (iii) to identify and characterise farm types based on packages of RAP which farmers have adopted. Examining the impact of farmers' participation in a joint experimentation may be crucial in informing decisions on how yield enhancing technologies for rice could be delivered to farmers to ensure adoption and realisation of expected results.

Materials and methods

Study area

The study was conducted in the Doho rice irrigation scheme, where components of recommended agronomic practices (RAP) for rice had been previously tested in researcher led on-farm field trials designed and managed together with farmers (Awio et al., 2022). The Doho rice irrigation scheme is located in Eastern Uganda in the Butaleja district[1] (34°02′ E, 0°56′ N). It is the largest public rice irrigation scheme in Uganda (Wanyama et al., 2017), covering an area of 1,000 ha, of which 952 ha is cultivated by over 4,000 smallholder farmers. It lies at an altitude of 1,100 m a.s.l. and belongs to the Lake Kyoga basin agroecological zone. It receives irrigation water from River Manafwa that originates from Mt. Elgon. The annual average rainfall in the area is 1,186 mm, distributed over two rainy seasons, from March to May and from August to October. The annual average temperature here is 22.7°C, with daily mean temperatures ranging from 15.4°C to 30.7°C (Namyenya, 2014). The scheme is divided into 11 blocks, each block sub-divided into 5–15 strips, and each strip having 20–30 farmers. Rice varieties commonly grown by farmers within the scheme are K 98 and K 85.

Data types and data collection

A semi-structured questionnaire was used to collect comprehensive information from smallholder rice farmers in the study area. Field observations were made at the time of field visits after individual farmer interviews to collect information on farmers' crop management practices and grain yield. Pre-testing of the semi-structured questionnaire was done at the beginning of January 2021 with 7 farmers within the scheme. The questionnaire was then refined and revised with closed and open-end questions to improve further discussion with respondents. In total, 146 rice farmers distributed across 6 sub-counties, 20 parishes and 41 villages of the Butaleja district were interviewed face-to-face in the local language (and only for the literate farmers upon indicating preference, English was used) by specifically trained enumerators from mid-January to the start of May 2021. Of these 146 farmers, 86 were part of the 114 farmers who participated in the joint experimentation of 2019 (herein referred to as participating farmers) and 60 had not taken part in the joint experimentation (herein denoted as non-participating farmers). These latter 60 farmers were purposively selected, as a control group to compare with the participating farmers, based on records from block leaders and willingness to take part in the study, to include farmers considered to be from poor, medium and rich socio-economic backgrounds. All farmers who participated in this study were those who were in production and were to harvest their rice within the time frame of the study to make assessment of crop management practices and grain yield in farmers' fields possible. The study was conducted with informed oral consent by all respondents. Confidentiality of all information collected was guaranteed and research protocols ensured that it was impossible to link published, aggregated data to individual respondents. Applicable guidelines and regulations for survey ethics were diligently followed. No ethical approval prior to the study was obtained as this was not required in Uganda.

The collected information (Table 1) included characteristics of the farm household head and farmer (name, gender, age, education), household size, farm size (total household land area, total land area under rice production), herd size (total herd size, number of cattle, small ruminants and poultry), farmer's participation in the joint experimentation, information on family and hired labour for rice production, duration in rice growing, and on rice management practices including adoption of all specified RAP (cf. Table 1), seed source, grain yield, and market price for paddy and milled rice. Cropping area was recorded in acres and converted to hectares for reporting (1 ha being equal to 2.47 acres). All costs were recorded in Ugandan Shillings (UGX) and where it is converted to US Dollar for reporting the exchange rate of May 2021 was used (1 USD = 3,530 UGX). For grain yield estimation, a survey plot of 10 m × 10 m within each farmer's field was marked from the centre of the field during field observations and a net plot of 4 m × 4 m from within the 10 m × 10 m plot was defined for final yield assessment. At harvest all panicles from the net plot were cut using a sickle, threshed, sun-dried, and the grains winnowed to remove empty grains. Grain weight and moisture content were measured using a digital weighing scale (Mini Crane scale model MNCS-M) and moisture metre (SATAKE Moistex Model SS-7). Rice grain yield adjusted to 0% moisture content (dry weight) was expressed in kg ha^{-1}.

Data analysis

To assess differences in management practices and grain yield among all farmers, data were subjected to analysis of variance (ANOVA) using an unbalanced treatment structure in Genstat (19th edition) at 5% probability, taking the different farmers' fields as blocks. Where differences were significant, treatment means were separated using Fisher's least significant difference (LSD) test. A paired *t*-test was done for participating farmers to assess individual farmer's yield gain after participation in the joint experimentation. To quantify the effect of change in management practices of participating farmers after joint experimentation on grain yield, regression analysis using Generalised Linear Model was used. The exploitable yield gap

1 A district in Uganda is the local government administrative unit, divided into counties, sub-counties, parishes and villages.

TABLE 1 Description of variables, units, and minimum and maximum values of variables used in the principal component analysis (PCA) and cluster analysis (CA), and the subsequent characterisation of farm types.

Name of variable	Description and units	Minimum	Maximum
Field levelling	= 1 if yes, 0 if no	0	1
Use of certified seed	= 1 if certified seed, 0 if farmer-saved seed	0	1
Use of fertiliser in the nursery bed	= 1 if yes, 0 if no	0	1
Transplanting time	= days of transplanting rice seedlings after sowing the nursery (DAS)	21	46
Timely transplanting	= 1 if transplanting is done up to 28 DAS, 0 if transplanting is done after 28 DAS	0	1
Line transplanting	= 1 if line transplanting, 0 if random transplanting	0	1
Gap-filling	= 1 if yes, 0 if no	0	1
Use of fertiliser in the field	= 1 if yes, 0 if no	0	1
Weeding time	= days of weeding after transplanting (DAT)	15	70
Timely weeding	= 1 if weeding is done up to 21 DAT, 0 if weeding done after 21 DAT	0	1
N rate	= amount of N applied in kg ha^{-1}	0	68.2
Timely fertilisation	= 1 if fertilisation is done up to 30 DAT, 0 if fertilisation is done after 30 DAT	0	1
Fertilisation time	= days fertiliser is applied after transplanting (DAT)	7	60
Organic (rice straw) input	= 1 if rice straw is incorporated in the soil during ploughing, 0 if not	0	1
Age of household head	= household head's age in years	22	82
Gender of household head	= 1 if male, 0 if female	0	1
Household head's education	= 1 if higher than primary school, 0 if no education or primary education	0	1
Age of farmer	= farmer's age in years	20	80
Gender of farmer	= 1 if male, 0 if female	0	1
Farmer's education	= 1 if higher than primary school, 0 if no education or only primary education	0	1
Farmer participated in joint experiment	= 1 if yes, 0 if no	0	1
Household size	= total number of household members	2	35
Family labour	= average number of household members ha^{-1} season^{-1}	1	128
Hired labour	= average number of people hired ha^{-1} season^{-1}	0	124
Cost of hired labour	= average amount of money spent on hired labour ha^{-1} season^{-1} in UGX × 10^6	0	2.5
Herd size[a]	= total number of livestock in tropical livestock unit (TLU)	0	8.9
Small ruminant ratio	= share of small ruminants (goats and sheep) in total herd size	0	1
Poultry ratio	= share of poultry (chicken) in total herd size	0	1
Total value of livestock	= value of cattle, goats, chicken, sheep and pigs combined in UGX × 10^6	0	16.8
Total household land area	= hectares of land owned by household	0	6.48
Total value of land	= value of land owned by household in UGX × 10^6	0	64.0
Total land area for rice growing	= hectares of land used for rice growing	0.1	3.24
Land tenure for rice growing	= 1 if owned, 0 if rented or borrowed	0	1
Grain yield[b]	= rice grain yield in kg ha^{-1} dry weight	1,930	5,905
Price of paddy	= selling price of paddy in UGX kg^{-1}	600	1,100
Price of milled rice	= selling price of milled rice in UGX kg^{-1}	1,200	2,500
Total income from rice per year per farm[c]	= total cash income from selling all rice harvest in UGX year^{-1} ha^{-1} × 10^6	2.96	25.7
Duration in rice growing	= number of years the farmer has been engaged in rice growing	2	38
Attended training/advise on rice farming	= 1 if yes, 0 if no	0	1
Other crops	= total annual household income from other crops in UGX × 10^6	0	7.0
Livestock	= total annual household income from livestock in UGX × 10^6	0	8.6
Employment	= total annual household income from formal employment in UGX × 10^6	0	7.0
Causal labourer	= total annual household income from informal employment (UGX × 10^6)	0	1.4
Business	= total annual household income from business (UGX × 10^6)	0	5.87

(Continued)

TABLE 1 (Continued)

Name of variable	Description and units	Minimum	Maximum
Crop sale ratio	= share of income from sale of crops	0.36	1.00
Livestock sale ratio	= share of income from sale of livestock	0	0.33
Off-farm income ratio	= share of combined income from formal employment, casual labour and business	0	0.64

Variables in bold are the ones used in the PCA and clustering.
RAP, recommended agronomic practices.
[a]Tropical livestock unit (TLU) is taken to be an animal of 250 kg live weight (Jahnke et al., 1987).
[b]Estimated from the 4 m × 4 m net plot.
[c]Income estimate reported by the farmer, not calculated from estimated grain yield; number of observations (n) = 146.

(i.e., the difference between attainable farm yield and actual farm yield) was estimated using the top decile approach (Stuart et al., 2016). Attainable farm yield was defined as the mean yield of the top 10-percentile of yields from all farmers' fields after joint experimentation, and actual farm yield was taken as the mean yield of participating and non-participating farmers. To evaluate the differences in management practices and grain yield of participating farmers, these farmers were grouped based on grain yield in (i) farmers' practice (FP) plot and (ii) recommended agronomic practice (RAP) plot during the joint experimentation. Based on FP plot yield, farmers were categorised as lower-yielding (with grain yields between 1,364 and 3,037 kg ha^{-1} dry weight, $n = 28$), middle-yielding (with grain yields varying from 3,048–4,050 kg ha^{-1} dry weight, $n = 29$) and top-yielding (with grain yields ranging from 4,065–5,545 kg ha^{-1} dry weight, $n = 29$) third during the joint experimentation. Based on RAP plot yield, farmers were grouped as those who had higher yield in RAP plot compared with FP plot (i.e., RAP yield > FP yield: RAP and FP yield ranged from 2,210 to 5,753 and 1,364 to 5,545 kg ha^{-1} dry weight, respectively, $n = 69$) and those who had higher FP plot yield compared with RAP plot yield (i.e., FP yield > RAP yield: FP and RAP yield ranged from 3,048 to 4,825 and 2,875 to 4,255 kg ha^{-1} dry weight, respectively, $n = 17$) during the joint experimentation.

To construct farm typologies, where combined data for participating and non-participating farm households were used, SPSS (Statistical Package for the Social Sciences), version 25.0 was used to analyse the data following a multivariate method. A principal component analysis (PCA) was first used to reduce the number of variables into a new set of components. Eight variables related to components of RAP (i.e., field levelling, use of certified seed, use of fertiliser in the nursery bed, timely transplanting, line transplanting, gap-filling, use of fertiliser in the field, and timely weeding) were chosen for the PCA. Three principal components exceeding an eigenvalue of 1.00, according to Kaiser's criterion, were retained accounting together for 50.1% of the total variance (Supplementary Table S1). Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy indicated the sample was adequate (value of 0.56) and Bartlett's test of sphericity ($p = 0.008$) showed that the analysis would be valid. Evaluating the correlations between the variables and the three components, a loading of >0.50 was considered. With the identified components, a hierarchical, agglomerative cluster analysis (CA) was done using Ward's method to minimise the variance within a cluster and squared Euclidean distance to measure the distances. After clustering farms based on the components of RAP applied, one-way ANOVA was used to test for significant differences between clusters for variables in the categories: RAP components adopted, socio-economic characteristics, rice production and farming knowledge, and other sources of income (Table 1). Differences in means between the clusters were separated using Fisher's LSD test. The proportion of participating and non-participating farm households in each identified cluster or farm type was determined. Analysis of household characteristics for participating and non-participating farmers in each cluster was made where results indicated households under a given cluster, whether participating or non-participating farm households, were identical (Supplementary Table S2).

Results

Grain yield and management practices of participating farmers

Participating farmers that had lower (lower-yielding third), moderate (middle-yielding third) and higher (top-yielding third) yields under FP during joint experimentation likewise observed significantly different yields after experimentation ($p = 0.03$, SED = 169). Top-yielding farmers during joint experimentation also had the highest mean yield 1 year later (4,379 kg ha^{-1}), followed by middle (4,039 kg ha^{-1}) and lower (3,951 kg ha^{-1}) yielding farmers who had similar yields (Figure 1A). Average yields during experimentation had been 4,471, 3,566 and 2,593 kg ha^{-1}, respectively, for the top-, middle- and lower-yielding farmers ($p < 0.001$, SED = 98.5). Median yields after experimentation were 4,458, 4,161 and 3,895 kg ha^{-1}, against 4,323, 3,589 and 2,772 kg ha^{-1} during experimentation, respectively, for the top-, middle- and lower-yielding farmers (Figure 1A). Despite having lower grain yield,

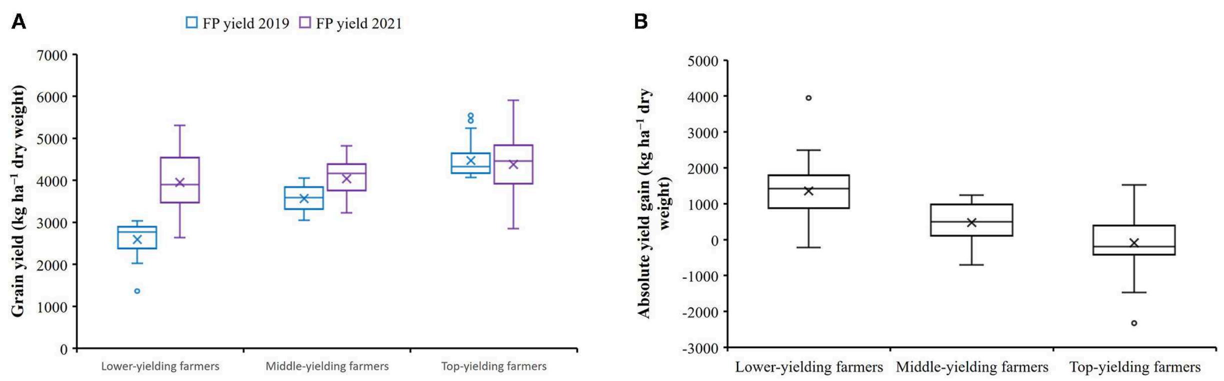

FIGURE 1
Distribution of grain yield during and after joint experimentation **(A)**, and yield gain of farmers 1 year after participation in joint experimentation **(B)**. Absolute yield gain was calculated as the difference between grain yield under FP (farmers' practice) 1 year after and during joint experimentation. FP yield 2019: FP yield during joint experimentation in 2019; FP yield 2021: FP yield in 2021, 1 year after joint experimentation; Lower- ($n = 28$), middle- ($n = 29$) and top- ($n = 29$) yielding farmers are grouped based on yield obtained under FP during joint experimentation.

lower-yielding farmers observed a significantly ($p < 0.001$, SED = 199) higher yield gain compared with the middle- and top-yielding farmers (Figure 1B; Supplementary Table S3). A paired *t*-test indicated that at individual farmer's field, average yield gain was 1,358 kg ha^{-1}, ranging between 1,027 and 1,689 kg ha^{-1} for the lower-yielding farmers ($p < 0.001$). This gain was on average 473 kg ha^{-1} for the middle-yielding farmers, ranging between 252 and 695 kg ha^{-1} ($p < 0.001$). Top-yielding farmers had on average −91.7 kg ha^{-1} yield gain, ranging from −397 to 213 kg ha^{-1} ($p = 0.54$) (Supplementary Table S3).

A multiple linear regression showed that change in grain yield after joint experimentation was influenced by change in weeding time and the combined effect of change in fertilisation timing and N rate, accounting for overall 41% of the yield gain observed (Table 2). Weeding and fertilisation by 1 day earlier on average increased grain yield by 40.9 and 11.6 kg ha^{-1} day^{-1}, respectively. Increasing N amount by 1 kg ha^{-1} resulted in 16.6 kg ha^{-1} increase in grain yield (Table 2). There was a significant difference ($p < 0.001$, SED = 3.20) in change of weeding time among the farmers, explaining the observed differences in yield gain. Lower-yielding farmers improved their weeding time by weeding on average 2 days earlier (ranging from 2 days later to 6 days earlier) after experimentation compared with weeding time in the FP plot during experimentation. Middle- and top-yielding farmers weeded on average 8 (range: 3–12) and 14 (range: 9–19) days later, respectively, after experimentation compared with weeding time in the FP plot during experimentation (Table 3). Overall, the majority (61%) of lower-yielding farmers weeded earlier than their weeding time in the FP plot during joint experimentation, compared with 24 and 7% of middle- and top-yielding farmers, respectively (Figure 2). In all, weeding time delay compared with recommended weeding time, after experimentation, was not different among farmers ($p > 0.05$, SED = 2.76), with average weeding delay of 14, 15 and 15 days, respectively, for the lower-, middle- and top-yielding farmers (Figure 3). During experimentation, this weeding delay was significantly different among farmers ($p < 0.001$, SED = 1.76), where lower-, middle- and top-yielding farmers had an average weeding delay of 16, 8 and 3 days, respectively. Lower-yielding farmers also had a slightly larger N rate increase of 19.7 kg ha^{-1} compared with 16.0 and 12.2 kg ha^{-1} increase in N rate for the middle- and top-yielding farmers, after experimentation, respectively (Table 3).

Analysis of household socio-economic characteristics of lower-, middle- and top-yielding farmers showed no major difference among households that could explain differences in yield or yield gain among farmers. Even though lower-yielding farm households had significantly smaller household size, fewer small ruminants and less income from other crops compared with middle- and top-yielding farm households (Table 4), these differences were small and populations overlapped. Likewise lower-yielding farm households had smaller herd size, land size, area under rice production and a larger income from off-farm activities, however, these differences were not significant among groups. The lack of clear differences among farm households could indicate that all these farmers have the potential to achieve the higher yield levels attained by top producers under their current production system.

To test if farmers who had, during the joint experimentation, a higher yield in their FP plots than their RAP plots would differ in yield and practices from farmers who had a lower yield in their FP plots than their RAP plots, these two groups were analysed separately. Farmers who had higher yield on their FP plot compared with their RAP plot during joint experimentation also had on average higher yields after experimentation (4,385 kg ha^{-1}, median 4,401 kg ha^{-1}) than farmers who had lower yield under FP plot compared with RAP plot during joint experimentation (4,061 kg ha^{-1}, median

TABLE 2 Slopes of linear regression lines relating change in grain yield on farmers' fields and change in management practices of farmers after participation in joint experimentation, Doho rice irrigation scheme, Butaleja District, Uganda, 2021.

Management practice	Slope estimate	Unit of slope estimate	Standard error	*p*-value	Lower 95% confidence limit	Upper 95% confidence limit	Adjusted R^2
Weeding time (DAT)	40.9	kg ha^{-1} day^{-1}	6.23	<0.001	28.6	53.3	0.33
N (kg ha^{-1})	16.6	$\frac{\text{kg grain ha}^{-1}}{\text{kg N ha}^{-1}}$	5.83	0.01	5.03	28.2	0.08
Fertilisation timing (DAT)	11.6	kg ha^{-1} day^{-1}	5.51	0.04	0.63	22.5	0.04
Transplanting time (DAS)	8.7	kg ha^{-1} day^{-1}	20.3	0.67	−31.7	49.1	0.00
+ Weeding time (DAT)	39.6	kg ha^{-1} day^{-1}	5.86	<0.001	27.9	51.3	0.41
+ Fertilisation timing × N rate	0.51	$\frac{\text{kg ha}^{-1}\text{ day}^{-1}}{\text{kg N ha}^{-1}}$	0.15	<0.001	0.22	0.80	

DAT, days after transplanting; DAS, days after sowing; number of observations (n) = 86.

TABLE 3 Grain yield and management practices during (2019) and after (2021) joint experimentation separately for the same farmers with lower, middle and higher yields during joint experimentation in 2019.

Parameter		During experimentation (2019)			After experimentation (2021)		
		Lower	Middle	Top	Lower	Middle	Top
Grain yield (kg ha^{-1})		2593[a]	3566[b]	4471[c]	3951[a]	4039[a]	4379[b]
Weeding time	14–21 DAT (%)	3.6	17.2	65.5	3.6	13.8	13.8
	22–28 DAT (%)	0	24.2	20.7	25.0	13.8	24.1
	≥29 DAT (%)	96.4	58.6	13.8	71.4	72.4	62.1
Average weeding time (DAT)		36.5[c]	28.4[b]	22.0[a]	34.6	36.1	35.8
Fertiliser use	Yes (%)	17.9[a]	27.6[a]	55.2[b]	78.6	75.9	79.3
	No (%)	82.1	72.4	44.8	21.4	24.1	20.7
Average N amount (kg ha^{-1})		4.44[a]	6.84[a]	14.7[b]	24.1	22.9	26.9
Fertilisation time	14–21 DAT (%)	0	0	6.2	9.1	27.3	21.7
	22–28 DAT (%)	0	12.5	25.0	27.3	9.1	17.4
	≥29 DAT (%)	100	87.5	68.8	63.6	63.6	60.9
Average fertilisation time (DAT)		40.2[ab]	44.6[b]	32.9[a]	30.0	33.6	32.4
Crop establishment method	Line transplanting (%)	21.4	20.7	34.5	39.3	44.8	41.4
	Random transplanting (%)	78.6	79.3	65.5	60.7	55.2	58.6
Transplanting time	21–28 DAS (%)	25	27.6	20.7	25	20.7	41.4
	29–35 DAS (%)	75	69.0	72.4	50	62.1	44.8
	≥36 DAS (%)	0	3.4	6.9	25	17.2	13.8
Average transplanting time (DAS)		29.6	29.7	30.7	31.9	31.8	30.9

DAT, days after transplanting; DAS, days after sowing.
Values within a row and experiment timing followed by a same letter are statistically the same according to Fisher's *post-hoc* test; when no letters are provided differences were not significantly different.
For the lower-, middle- and top-yielding farmers, numbers of observations (n) were 28, 29 and 29, respectively, during and after joint experimentation.

4,153 kg ha^{-1}), (Figure 4A). However, this yield difference was statistically marginal ($p = 0.07$, SED = 176). During the joint experimentation the average FP yields of these two groups was 3,922 (median 3,854) and 3,464 (median 3,313) kg ha^{-1}, respectively ($p = 0.05$, SED = 227). Overall, average yield gain by farmers after joint experimentation was 571 kg ha^{-1}, varying between 366 and 776 kg ha^{-1} (Supplementary Table S3). The yield gains were not different ($p = 0.61$, SED = 260) between these two groups of farmers (Figure 4B; Supplementary Table S3). At individual farmer's field, a paired t-test showed an average yield gain of 597 (median 630, value ranging between 348 and 846) and 463 (median 420, values ranging 200–727) kg ha^{-1}, respectively, for farmers who had lower and higher yields under FP plot compared with RAP plot during the joint experimentation (Figure 4B; Supplementary Table S3). All management practices a year after

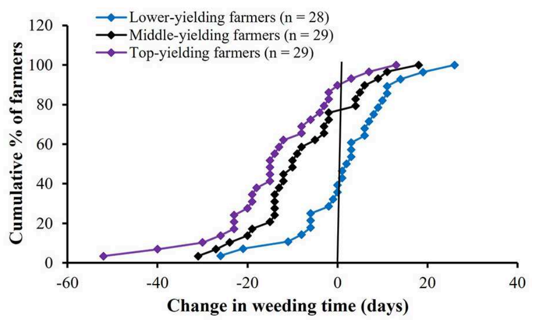

FIGURE 2
Change in weeding time by farmers after joint experimentation, Doho 2021. Change in weeding time was calculated as the difference between weeding time in FP plot during (2019) and after (2021) joint experimentation, days after transplanting (DAT). Minus (–) value implies that weeding time after experimentation was later compared with weeding time in FP plot during experimentation.

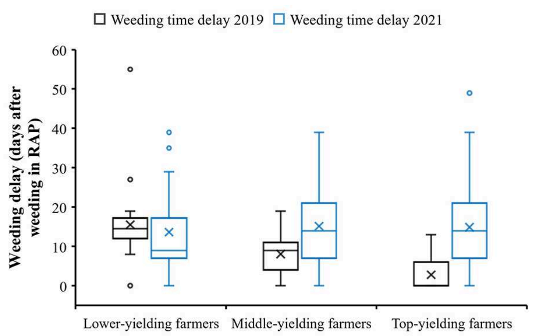

FIGURE 3
Weeding time delay compared with weeding time under recommended agronomic practices (RAP) during (2019) and after (2021) joint experimentation. Weeding time delay was calculated as the difference in weeding time under FP and RAP. Weeding time delay 2019: weeding delay during joint experimentation in 2019; Weeding time delay 2021: weeding delay after joint experimentation in 2021; Lower- ($n = 28$), middle- ($n = 29$) and top- ($n = 29$) yielding farmers are grouped based on yield obtained under FP during joint experimentation. For the top-yielding farmers in 2019, median was zero delay and negative weeding time delay is not possible, hence a lower whisker is absent.

the joint experimentation were similar among these two groups except weeding time, where 35% of farmers who had higher yield under FP plot compared with RAP plot weeded within 21 DAT, with an average weeding time of 30 DAT ($p < 0.001$, SED = 0.08). This was only 4% for farmers who had lower yield under FP plot compared with RAP plot, with an average weeding time of 37 DAT.

Grain yield and management practices of participating and non-participating farmers

Grain yield varied significantly among farmers who participated (participating farmers) and those who did not participate (non-participating farmers) in the joint experimentation ($p = 0.05$). Participating farmers had a higher grain yield, averaging 4,125 kg ha^{-1} compared with 3,893 kg ha^{-1} average grain yield for non-participating farmers (SED = 117). Median yield was 4,184 kg ha^{-1} for participating farmers, with grain yield ranging between 2,636 and 5,905 kg ha^{-1}. Median yield was 3,971 kg ha^{-1} for non-participating farmers, and grain yield varied from 1,930 to 5,423 kg ha^{-1} (Figure 5). The exploitable yield gap was 20.0 and 24.5%, respectively, for participating and non-participating farmers, when the average of top-decile yield from all farmers' fields after joint experimentation (5,158 kg ha^{-1}) was taken as attainable farm yield.

We observed differences in some management practices between participating and non-participating farmers. Sixteen percent of participating farmers used certified seed, and 28% transplanted timely, with average transplanting time of 32 DAS, compared with 3 and 13% for non-participating farmers, respectively (Table 5). Differences in weeding time (36 vs. 39 DAT) and N amount (24.3 vs. 19.8 kg ha^{-1}) were statistically marginal ($p = 0.07$), between participating and non-participating farmers. Analysis of household data showed no difference among participating and non-participating farm households, except for training on rice farming which was significantly different ($p < 0.001$). More participating farmers (93%) had attended training related to rice production than non-participating farmers (50%) (Table 5). Participating farmers had also spent slightly more years in rice growing than non-participating farmers.

Farm households characteristics, farm types and characterisation from clusters

Analysis of household socio-economic data indicated that 86% of the farm households were male headed, with 40% of household heads having attained education higher than primary level (Table 6). The average farmer's age was 40 years and 42% of the farmers had attained education higher than primary school. Total household size was on average 10.2 persons. Farmers had on average 1.20 ha of farmland, of which 0.47 ha was under rice production. In terms of labour input in rice production, family and hired labour per rice growing season per ha was on average 22 persons. Regarding application of recommended agronomic practices for rice, 73% of farmers used fertiliser in the nursery bed, 22% transplanted timely (within 28 DAS rice seeds in the

TABLE 4 Household socio-economic characteristics of lower-, middle- and top-yielding farmers, Doho rice irrigation scheme, Butaleja District, Uganda, 2021.

Characteristic	Lower ($n = 28$)	Middle ($n = 29$)	Top ($n = 29$)	SED	*p*-value
Household characteristics					
Household head's education	0.36	0.48	0.41	0.13	0.64
Farmer's education	0.46	0.48	0.34	0.13	0.53
Duration in rice growing (years)	17.6	17.8	17.8	3.01	0.99
Attended training on rice farming	0.96	0.90	0.93	0.07	0.61
Household size	8.75^{a}	12.6^{b}	10.2^{ab}	1.55	0.05
Herd size (TLU)	0.87	1.81	1.71	0.46	0.09
Number of small ruminants (TLU)	0.13^{a}	0.32^{b}	0.22^{ab}	0.08	0.05
Total livestock value ($\times 10^6$ UGX)	1.15	2.56	2.44	0.86	0.20
Total household land area (ha)	0.96	1.38	1.32	0.29	0.30
Total value of household land ($\times 10^6$ UGX)	9.45	13.4	12.3	3.05	0.43
Land area under rice growing (ha)	0.43	0.57	0.48	0.12	0.48
Labour in rice production					
Family labour ha^{-1} $season^{-1}$	17.7	25.5	18.5	5.30	0.28
Hired labour ha^{-1} $season^{-1}$	25.2	24.8	19.3	7.04	0.65
Cost of hired labour ha^{-1} $season^{-1}$ ($\times 10^6$ UGX)	0.62	0.85	0.66	0.14	0.24
Sources of income $year^{-1}$ ($\times 10^6$ UGX)					
Rice (net)	5.48	5.38	5.82	0.84	0.89
Other crops	0.24^{a}	0.67^{ab}	0.92^{b}	0.33	0.02
Livestock	0.28	0.54	0.53	0.29	0.60
Off-farm	1.47	0.99	0.90	0.50	0.48

Values within a row followed by a same letter are statistically the same according to Fisher's *post-hoc* test; when no letters are provided differences were not statistically significant; TLU, tropical livestock unit; n, number of farm households in each group.

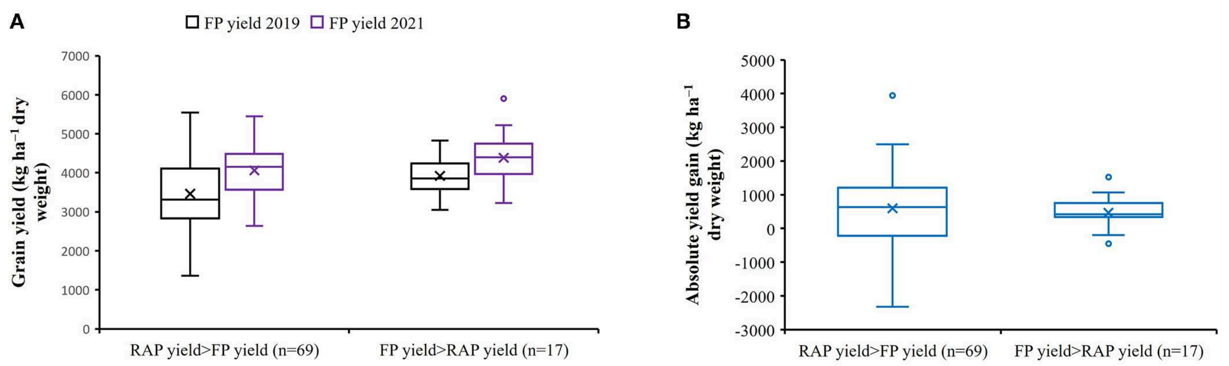

FIGURE 4
Distribution of grain yield during (2019) and after (2021) joint experimentation **(A)** and yield gain of farmers after participation in joint experimentation **(B)**. Absolute yield gain was calculated as the difference between grain yield under FP (farmer's practice) after and during joint experimentation. FP yield 2019: FP yield during joint experimentation in 2019; FP yield 2021: FP yield after joint experimentation in 2021; RAP yield > FP yield ($n = 69$): farmers who had lower yield under FP plot compared with RAP plot; and FP yield > RAP yield ($n = 17$): farmers who had higher yield under FP plot compared with RAP plot, during joint experimentation; RAP, recommended agronomic practices.

nursery), 36% used line transplanting, 76% applied fertiliser in the field, with an average N rate of 22.4 kg ha^{-1} and 12% weeded timely (within 21 DAT rice seedlings, Table 6). Only 11% of the farmers used certified rice seeds, while 98% did field levelling and 95% incorporated rice straw from the previous season into the soil.

Principal component analysis (PCA) and cluster analysis (CA) resulted in identification of three different clusters defined

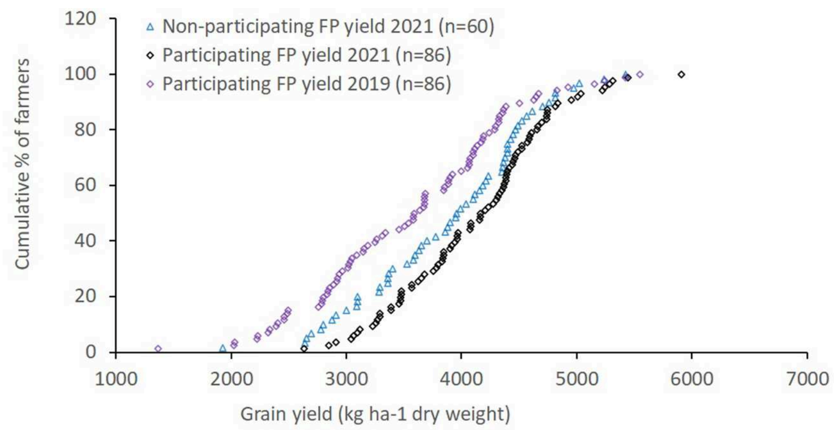

FIGURE 5
Cumulative distribution of grain yield of farmers after joint experimentation in 2021. Participating farmers are those who participated and non-participating farmers did not participate in the joint experimentation.

as farm types with their characteristics (Table 6). Cluster 1 (farms with less application of RAP) constituted the second largest cluster with 28% (n = 41) of the farms. Of the farmers in this group, 32% used fertiliser in the nursery, 15% transplanted timely, 5% transplanted in line, and 27% applied fertiliser in the field, with the lowest N amount of 7.8 kg ha^{-1}. In comparison to the other two clusters, these farmers had moderate land area under rice production (0.45 ha) and expended less cost. Average grain yield was the lowest for them at 3,761 kg ha^{-1}. However, net income from rice growing in these farms was slightly higher at 5,510,000 UGX (ca. 1,560 USD) year^{-1}; in addition to more income from off-farm activities at 1,060,000 UGX (ca. 300 USD). This cluster constituted 26 and 32%, respectively, of participating and non-participating farm households (Supplementary Table S2). Cluster 2 (farms with highest level of application of RAP) was the smallest cluster with 24% (n = 35) of the farms. In this group, 71% of the farmers used fertiliser in the nursery, 63% transplanted timely, 69% transplanted in line, and 94% applied fertiliser in the field, with the highest N application rate of 32.5 kg ha^{-1}. These farmers also had the largest land area under rice production (0.60 ha) and the highest production cost. Average grain yield was the highest at 4,342 kg ha^{-1}, however, with the lowest net income from rice production at 5,030,000 UGX (ca. 1,425 USD) year^{-1}, but the highest income from other crops. The lower income from rice production could be attributed to the higher expenditure on labour. Overall, these farms have more diversified sources of income compared with the other clusters. Thirty percent of participating and 15% of non-participating farm households made up this cluster. Cluster 3 (farms with moderate application of RAP) was the largest cluster with 48% (n = 70) of the total farms studied. Of the farmers in this cluster, 98% used fertiliser in the nursery, 6% transplanted timely, 39% used line transplanting, and 96% applied fertiliser in the field, with average N amount of 26.0 kg ha^{-1}. These farmers had slightly smaller land area under rice production (0.42 ha), with higher production cost. Grain yield was moderate in this cluster at 4,031 kg ha^{-1}, and leading to a net income from rice production of 5,500,000 UGX (ca. 1,560 USD) year^{-1}. Participating and non-participating farm households that made up the cluster were 44 and 53%, respectively (Supplementary Table S2).

Discussion

This study showed that top-yielding farmers during experimentation still had the highest average yield after experimentation compared with the lower- and middle-yielding farmers during experimentation. Yet, the lower-yielding farmers made the highest yield gains (Figure 1). The higher yield gains by the lower-yielding farmers could be attributed to a significant improvement in management practices after experimentation. Generally lower-yielding farmers improved their weed management, and fertiliser use, amount and timing (Table 3; Figure 2). Even though lower-yielding farmers made larger yield gains, the overall yields recorded by farmers are still low, for the rice variety grown, when compared with yields observed under researcher-managed on-farm trials in the same study area (Awio et al., 2021). Grain yields recorded in this study are, however, higher than yields earlier reported under farmers' practice in the study area (Senthilkumar et al., 2020; Awio et al., 2022). The lack of yield gain by the top-yielding farmers might imply that at their current management level these farmers could not further raise their grain yields beyond the level observed during joint experimentation, probably because the observed current N input could be too low (which was up to a maximum of 68 kg N ha^{-1} after experimentation from 46 kg N ha^{-1} maximum rate during experimentation), in

TABLE 5 Management practices and household socio-economic characteristics of participating and non-participating farmers, Doho rice irrigation scheme, Butaleja District, Uganda, 2021.

Characteristic	Participating farmers ($n = 86$)	Non-participating farmers ($n = 60$)	SED	p-value
Management practice				
Field levelling	0.98	0.98	0.02	0.78
Use of certified seed	0.16	0.03	0.05	0.01
Use of fertiliser in the nursery bed	0.73	0.73	0.07	0.99
Timely transplanting	0.28	0.13	0.07	0.04
Average transplanting time (DAS)	31.5	33.5	0.84	0.02
Line transplanting	0.42	0.28	0.08	0.10
Gap-filling	0.71	0.65	0.08	0.45
Use of fertiliser in the field	0.78	0.73	0.07	0.53
Timely fertilisation	0.66	0.70	0.09	0.60
Average fertilisation time (DAT)	32.0	30.8	2.03	0.56
Average N amount (kg ha^{-1})	24.3	19.8	2.54	0.07
Timely weeding	0.10	0.13	0.05	0.60
Average weeding time (DAT)	35.5	39.1	1.96	0.07
Household characteristics				
Farmer's education level	0.43	0.40	0.08	0.72
Attended training on rice farming	0.93	0.50	0.06	<0.001
Duration in rice growing (years)	17.7	14.4	1.82	0.07
Household size	10.6	9.58	0.97	0.32
Herd size (TLU)	1.47	1.02	0.27	0.10
Total household land area (ha)	1.22	1.16	0.19	0.72
Land area under rice growing (ha)	0.49	0.44	0.08	0.45
Family labour ha^{-1} $season^{-1}$	20.6	24.9	3.74	0.25
Hired labour ha^{-1} $season^{-1}$	23.1	19.9	3.96	0.42
Cost of hired labour ha^{-1} $season^{-1}$ ($\times 10^6$ UGX)	0.71	0.71	0.10	0.99
Income $year^{-1}$ ($\times 10^6$ UGX)				
Rice (net)	5.56	5.32	0.54	0.66
Other crops	0.61	0.33	0.18	0.12
Livestock	0.45	0.34	0.17	0.48
Off-farm	1.11	0.83	0.30	0.34

DAS, days after sowing; DAT, days after transplanting; TLU, tropical livestock unit; n, number of observations.

combination with lack of P and K application. It may therefore be necessary that farmers in this production system increase N rates, and P and K application be emphasised based on field inherent fertility to further raise grain yields as current farmers' fertilisation strategies do not put into consideration P and K application (Awio et al., 2022). This should be in addition to improved crop management practices, like proper timing of weeding and fertiliser application. Large yield gains have been reported in the same location under researcher management when N, P and K rates were increased from 80-40-40 to 100-50-50 kg ha^{-1} N, P and K, respectively (Awio et al., 2021). The results of our study are consistent with the findings of Ogada and Nyangena (2015) who observed higher yield gains, due to adoption of improved management practices, by farm households that had lower to medium grain yield than farm households at the upper end of the yield distribution. Shaibu et al. (2021) reported that the highest benefits from scaling up and adoption of improved management practices would be derived by low resource-endowed farm households. Similarly, Ainembabazi et al. (2018) showed that adoption of improved crop varieties would benefit poor farm households more than better-off households. However, in our present study there was no clear difference in resource endowment of lower, middle and top yielding farm households. Farmers who observed higher grain yield in their recommended agronomic practices (RAP) plot compared with their FP plot during experimentation realised larger yield gains than farmers who had lower yield under RAP compared with FP plot, an indication that the former

TABLE 6 Characteristics of farm households and the identified clusters including the *p*-value of one-way analysis of variance of differences between farm types.

Characteristic	Cluster 1 ($n = 41$)	Cluster 2 ($n = 35$)	Cluster 3 ($n = 70$)	Mean ($n = 146$)	*p*-value
Components of RAP adopted					
Field levelling	1.00[b]	0.91[a]	1.00[b]	0.98	0.01
Use of certified seed	0.02[a]	0.43[b]	0.00[a]	0.11	<0.001
Use of fertiliser in the nursery bed	0.32[a]	0.71[b]	0.98[c]	0.73	<0.001
Timely transplanting	0.15[a]	0.63[b]	0.06[a]	0.22	<0.001
Line transplanting	0.05[a]	0.69[c]	0.39[b]	0.36	<0.001
Gap-filling	0.68[a]	0.94[b]	0.56[a]	0.68	<0.001
Use of fertiliser in the field	0.27[a]	0.94[b]	0.96[b]	0.76	<0.001
Timely weeding	0.12	0.14	0.10	0.12	0.81
Timely fertilisation	0.55[a]	0.82[b]	0.63[a]	0.65	0.04
Average N amount (kg ha^{-1})	7.76[a]	32.5[c]	26.0[b]	22.4	<0.001
Organic input	0.93	0.97	0.94	0.95	0.70
Average transplanting time (DAS)	32.8[b]	28.9[a]	33.8[b]	32.3	<0.001
Average weeding time (DAT)	40.5[b]	32.0[a]	37.4[b]	37.0	0.01
Average fertilisation time (DAT)	35.8[b]	26.9[a]	33.1[b]	32.4	<0.001
Rice production and farming knowledge					
Grain yield (kg ha^{-1} dry weight)[1]	3,761[a]	4,342[c]	4,031[b]	4,030	0.001
Duration in rice growing (years)	15.8	17.6	16.1	16.4	0.75
Attended training in rice farming	0.63	0.86	0.77	0.75	0.07
Socio-economic characteristics					
Age of household head	45.4	47.2	44.3	45.3	0.64
Gender of household head	0.88	0.94	0.81	0.86	0.19
Household head's education	0.32	0.49	0.41	0.40	0.32
Age of farmer	41.9	40.9	38.7	40.1	0.50
Gender of farmer	0.63[ab]	0.83[b]	0.56[a]	0.64	0.02
Farmer's education	0.29	0.51	0.44	0.42	0.13
Farmer participated in OFT[2]	0.54	0.74	0.54	0.59	0.11
Household size	10.2	10.1	10.2	10.2	0.99
Family labour ha^{-1} $season^{-1}$	22.6	23.5	21.7	22.4	0.92
Hired labourer ha^{-1} $season^{-1}$	22.8	21.0	21.6	21.8	0.94
Total labour cost ha^{-1} $year^{-1}$ ($\times 10^6$ UGX)	2.48[a]	3.13[b]	3.03[b]	2.90	<0.001
Total household land area (ha)	1.17	1.49	1.06	1.20	0.17
Land area under rice growing (ha)	0.45	0.60	0.42	0.47	0.12
Herd size (TLU)	1.45	1.37	1.14	1.28	0.58
Cattle (TLU)	1.14	1.02	0.91	1.00	0.72
Small ruminants (TLU)	0.21	0.23	0.19	0.21	0.71
Poultry (TLU)	0.09[b]	0.11[b]	0.04[a]	0.07	<0.001
Income $year^{-1}$ ($\times 10^6$ UGX)					
Rice (net)	5.51	5.03	5.50	5.39	0.75
Other crops	0.25[a]	0.91[b]	0.43[a]	0.50	0.02
Livestock	0.42	0.62	0.30	0.41	0.27
Off-farm	1.06	1.05	0.93	1.00	0.91

[1]Estimated based on harvest from 16 m^2 within individual farmer's field.
[2]Joint experiment conducted on-farm in 2019.
Values within a row followed by a same letter are not statistically different according to Fisher's *post-hoc* test; when no letters are provided there were no statistical differences.
n, number of farm households in each cluster.

farmers learnt something from the joint experimentation which they were able to apply in their fields and make some gains in grain yields. Franke et al. (2010) in on-farm trials found that farmers copied management practices from experimental treatments, in some cases competing in terms of yield with the researcher-managed plots. This observation could point to the broader influence on-farm experimentation can have on farmer's yield improvements the subsequent seasons, something we observe in the present study.

Participating farmers had a slightly but significantly higher grain yield and application of some of the improved rice management practices compared with non-participating farmers (Figure 5; Table 5). This shows the potential benefit of exposing farmers to RAP, through participatory learning, on boosting rice yields in Uganda and similar rice production systems in sub-Saharan Africa. The findings further underscore the point that participating farmers learnt something from the joint experimentation and were able to apply that in their fields during the subsequent seasons, resulting in higher grain yields. Similar observation was made by Senthilkumar et al. (2018) who showed improvements in the implementation of RAP for rice by farmers and subsequently increased grain yields after participatory on-farm trials with farmers. Krupnik et al. (2012) and Senthilkumar et al. (2018) noted that farmers learnt by doing to better implement the components of RAP during the course of time the participatory trials were conducted. Kondylis et al. (2017) observed that directly training farmers resulted in a large increase in adoption of sustainable land management practices among farmers. Joint experimentation with farmers can therefore be an interesting way of directly training farmers where learning by doing is facilitated. This farmer training combined with farmers' own experiences with recommended agronomic practices can be used as a tool in rice farming extension efforts to transform rice production, triggering a positive change in the participating farmers' crop management practices, grain yield and livelihoods (Senthilkumar et al., 2018). This, however, requires an enabling environment for rice farmers to increase their production through the adoption of RAP components, for instance, improved access to certified seeds of high-yielding varieties and fertilisers at affordable prices, access to locally adapted simple weeding tools, and fair access to rice markets among others. Joint experimentation can also provide better feedback to research and extension on innovations or innovation components that will not work under local farmers' conditions.

The results of our study indicate that distinguished farm types varied in adoption of improved management practices for rice and grain yield, but not in resource endowment or socio-economic characteristics (Table 6). This may imply that farmers in this production system have the capacity of reaching a higher yield level when improved management practices are applied. The lack of difference in resource endowment among farm types could suggest that wealth is not an important factor in adopting improved management practices for rice in the current production system and rice scheme. Our study finding, however, contrasts with previous studies which reported household wealth and other socio-economic parameters to be key in adoption of innovations. For instance, a study of Urfels et al. (2021) in tropical Asia showed that household resource endowment determined timing of rice planting, in addition to ecosystem and climatic factors. In SSA, Chekene and Chancellor (2015), Nakano et al. (2018) and Nonvide (2021) noted that farmers' education, age, farming experience and training on improved rice production practices were important in the adoption of improved rice production technologies among rice farmers. Similarly, Fosso and Nanfosso (2016), Hassan et al. (2016) and Lulseged et al. (2016) showed household wealth, off-farm employment, farm size, participation in on-farm trials, and farmers' education to be associated with adoption of improved management practices for maize, e.g., improved weed management, improved seeds, and use of fertiliser. Likewise, Dersseh et al. (2016), Tadesse et al. (2017), and Tadesse et al. (2019) observed that adoption of improved potato varieties and production practices was related to household wealth and educational levels. In the present study, however, these variables were not significantly different among the identified farm types, except farmer's gender. Difference among farm types in attending trainings related to rice farming would be significant at 0.10% probability.

Conclusion

This study indicates that joint experimentation had a larger effect on raising yields of originally lower-yielding farmers and narrowed the yield gap between lower- and higher-yielding farmers, thus bringing farmers closer in their management and outputs. Lower-yielding farmers made more gains compared with higher-yielding farmers, an indication that lower-yielding farmers had more room to raise their yields, as it seemed difficult for higher-yielding farmers to further increase their yields. Despite the larger yield gains by lower-yielding farmers, the overall yields observed by farmers in the study area are still rather limited when compared with researcher-managed yields previously reported on-farm in the same rice scheme. No difference in household resource endowment was observed amongst farm types which could imply that wealth is not a crucial element of adoption of available innovation in this production system, unless all households were limited in further innovating. Further studies aimed at understanding the limitations to why some farmers do not apply packages of RAP despite not being socio-economically different from those farmers who apply, may be relevant to identify appropriate solutions to such bottlenecks hence boosting also these farmers' rice productivity.

Data availability statement

The data for this study are available upon reasonable request to the corresponding authors and under the condition that the identity of farmers involved can be protected.

Author contributions

Conceptualisation, methodology, and validation: TA and TJS. Data collection, formal analysis, and writing—original draft preparation: TA. Writing—reviewing and editing: TA, PCS, and TJS. 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.2022.1009469/full#supplementary-material

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Effects of intercropping sunn hemp into maize at different times and densities on productivity under rainwater harvesting technique

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Maize is a major food crop in Sub-Saharan Africa (SSA), and its productivity is affected by climate change-adaptive sustainable management practices. A 2-year field study (2019/20 and 2020/21 growing seasons) was carried out to evaluate the effect of sunn hemp (*Crotalaria juncea* L.) living mulch management on maize (*Zea mays* L.) production. Three sunn hemp planting periods were simultaneous with maize planting (P1), V15 maize growth stage (P2), and R1 maize growth stage (P3) and three densities 16.1 plants m^{-2} (D1-low), 32.1 plants m^{-2} (D2-medium), and 48.1 plants m^{-2} (D3-high). The intercrop components were planted in a split-plot treatment arrangement as an additive series with three replications and laid out in a randomized complete block design under the in-field rainwater harvesting (IRWH) technique. The growing season conditions revealed significant differences in rainfall distribution. Therefore, the planting period had highly significant ($p < 0.001$) effects on sunn hemp biomass, with an LSD value of 610.2 kg ha^{-1}, showing that the highest was obtained in P2 (2636.7 kg ha^{-1}) compared to P3 (811.3 kg ha^{-1}). However, the P3 treatment resulted in maize grain yield penalty, with yields as follows: P3 (2775.2 kg ha^{-1}), sole maize (3263.8 kg ha^{-1}), P2 (3281.9 kg ha^{-1}), and P1 (3287.8 kg ha^{-1}). P2 yielded a significantly ($p < 0.05$) high-income equivalent ratio of 2.09, indicating a 109% advantage for increasing farmers' income by integrating sunn hemp under the no-till area of IRWH. P1 and P2 sunn hemp planting periods are viable options for smallholder farmers in summer rainfall regions to improve economic benefits.

KEYWORDS

maize grain yield, biomass, planting period, plant density, income equivalent ratio, net benefits, living mulch

Highlights

- Sunn hemp was used as a living mulch in a rainwater harvesting maize-based system.
- Identification of optimum planting and density for sunn hemp can improve performance.
- Biomass and grain improved with simultaneous and V15 maize growth stage planting.
- The highest income equivalent ratio and net benefits were obtained at medium density.

Introduction

Maize (*Zea mays* L.) is a versatile multi-purpose crop that is primarily used as a feed crop worldwide, but it is also an important food crop for many developing countries, particularly those in Sub-Saharan Africa (SSA), Latin America and Asia. It is grown on 90 million hectares, accounting for over 300 million MT of production [Food and Agriculture Organization of the United Nations (FAOSTAT), 2018]. However, rainfed cultivation practiced by ∼90% of farmers in rural SSA and resource-constrained smallholder systems yields <1 t ha^{-1} of maize grain (Nyakudya and Stroosnijder, 2011; Van Ittersum et al., 2016; Njoroge et al., 2018). Rainfed production is unreliable in semiarid regions worldwide due to water scarcity caused by low rainfall and uneven distribution throughout the season. The yield varies significantly from year to year due to high precipitation variations. SSA country average yields for dryland maize ranged from 1.68 to 1.99 t ha^{-1} over a 9-year (2007–2016) (Food and Agriculture Organization of the United Nations (FAOSTAT), 2018). In-field rainwater harvesting techniques for drylands crop production have been implemented in many arid and semiarid regions worldwide to reduce future water scarcity.

In-field rainwater harvesting techniques describe the collection, storage, and use of rainwater runoff for crop production (Oweis and Taimeh, 1996). "*In-situ*" rainwater harvesting systems, also known as soil and water conservation systems, can increase the amount of water stored in the soil profile by holding rainwater where it falls (Salem et al., 2015). Deep tillage, contour farming, and ridging are common *in-situ* techniques that eliminate the separation of rainwater collection and storage areas. Micro-catchment techniques involve the construction of small structures across land slopes which collects surface runoff from the untilled-overland flow on short catchment lengths within the field and store in plant zone for subsequent plant use (Hensley et al., 2000). The ridge and furrow micro catchment water harvesting increased soil water content and grain yields (Liu et al., 2018; Wang et al., 2018). Several studies have investigated the benefits of micro-catchment techniques in crop production (Tabor, 1995; Zougmoré et al., 2003; Hensley et al., 2011). The in-field rainwater harvesting (IRWH) technique consists of a 2 m runoff strip and 1 m collection into the basin (Hensley et al., 2000; Botha et al., 2003, 2015). However, runoff strip requirement is associated with a loss of land area, which could be used for crop production compared to conventional tillage practices (Dzvene et al., 2021).

The suitability of the IRWH technique is thus argued to be related to local rainfall and soil profile characteristics, but management practices such as mulching and cropping system diversification can significantly improve its efficiency (Botha et al., 2003; Mzezewa et al., 2011; Tesfuhuney et al., 2015). With the IRWH technique, maize yields are affected by the amount and distribution of rainfall, with low precipitation (or severe drought years) resulting in low yields because there may be no runoff to collect (Botha et al., 2015; Dzvene et al., 2021). However, complementary management practices with varying mulching materials (Botha, 2006) or mulching levels (Tesfuhuney et al., 2015) improved maize productivity. Thus, the technique can be more effective in semiarid, drought-prone regions. According to the recommended application of the technology, Hensley et al. (2000) argued that the potential for yield enhancement is limited to clayey soils with a shallow profile. However, improvements in maize production were realized on fine sandy soil with high silt content and a B horizon profile that limits water movement (Tesfuhuney et al., 2015).

In contrast to conventional full area tillage, the technique provides yield benefits in different soils during dry years due to improved soil water storage (SWS) and reduced plant population because crops are only established in tramlines. The IRWH technique has been shown to increase maize, sunflower (*Helianthus annuus*), and dry bean (*Phaseolus vulgaris*) yields by 40, 30, and 90%, respectively (Botha et al., 2003). As evidenced by high evaporation losses in the runoff strip (Botha et al., 2003; Tesfuhuney et al., 2015), the improved water conditions are not limited to the basin area. In the Mzezewa et al. (2011) study to improve sunflower yield under the IRWH technique, cowpea (*Vigna unguiculata*) was incorporated as a living mulch using a row replacement intercropping series. Intercropping sunflower with cowpea resulted in grain yield reduction by 39.5–82.8% compared to the sole sunflower (Mzezewa et al., 2011). However, additional research using additive intercropping series is essential for integrating cover crops as living mulches. This can promote the utilization of the no-till strip to compensate for the associated land loss with IRWH and thus necessitates the careful selection of a multipurpose living mulch species, such as sunn hemp.

Sunn hemp (*Crotalaria juncea* L.) is native to India and grown for fiber, forage, and cover crop (Balkcom and Reeves, 2005; Mosjidis and Wehtje, 2011; Parenti et al., 2021). Sunn hemp is a drought-tolerant legume crop, requiring low rainfall (≈200 mm) to grow successfully (de Oliveira Miranda et al., 2020; Subrahmaniyan et al., 2021). The crop grows well in well-drained alluvial soils with sandy loam or loamy texture (Baligar and Fageria, 2007; Ashworth et al., 2015). In terms of biomass productivity, sunn hemp produces in the range of 2,500–4,000 kg ha^{-1} in 60–75 days, improving soil organic carbon and nitrogen, and can outperform cowpea, pigeon pea (*Cajanus cajan*), and other tropical legume cover crops (Akanvou et al., 2001; Baligar and Fageria, 2007; Baraibar et al., 2018). It is an economical crop under dryland because of its enhanced water and nutrient conservation in the soil (Sharma et al., 2010) and its ability to fix biological nitrogen in the soil (150–165 kg ha^{-1}). In SA, *C. juncea* is usually cultivated as green manure, fodder, or blast fiber crop (Cook et al., 1998). Maize grain yield was not affected by the relay intercropping of sunn hemp in a warm temperate region of SA (Murungu et al., 2011). Sunn hemp cover crop increased maize grain yield by 8–27% in the absence of nitrogen (N) fertilization (Jeranyama et al., 2000). Therefore, sunn hemp has been used as a cover crop before or simultaneously with maize cropping systems.

Identifying a suitable planting date is one of the efficient strategies in rainfed agriculture to avoid living mulch competition with the main crop (Lawson et al., 2015). Dry spells caused by erratic rainfall distribution and occurrences of a short growing season, on the other hand, can jeopardize the growth of living mulches if they are planted late in the season. Intercropping velvet bean [*Mucuna pruriens* (L) DC], fish bean (*Tephrosia vogelii* Hook.f.), blue lupin [*Lupinas angustifolius* var. angustifolius (L)], hairy vetch (*Vicia villosa* Roth.), common oat (*Avena sativa* L.), and rhodes grass cv Katambora (*Chloris gayana* Kunth) as late as 8 weeks after planting maize compromised their biomass productivity (Mhlanga et al., 2016). Changing a cover crop's planting date in other climates was shown to affect its growth, biomass yield, and main crop yield (Mirsky et al., 2011; Lawson et al., 2015). Therefore, appropriate economically viable living mulch planting dates may allow smallholder farmers to diversify cropping systems and increase economic efficiency. Crop diversification among smallholder farmers has been linked to relative income stability, but may have a negative impact on farm economic efficiency due to intra-seasonal climate variability (Ponce, 2020). The current study hypothesized that optimum planting dates and densities of sunn hemp living mulch in a no-tillage maize under IRWH will increase the biomass and grain yield productivity and enhance the economic returns of smallholders in semiarid areas of SA. Therefore, this study, investigated how planting periods (P) and densities (D) of sunn hemp living mulch affected growth parameters, biomass, maize grain yields, and economic returns in a maize-based system under the IRWH technique.

Materials and methods

Experimental site and design

This study was conducted during 2019/2020 and 2020/2021 growing seasons at the Kenilworth Experimental Research Farm, University of the Free State (UFS) near Bloemfontein (Latitude 29°01′S, Longitude 26°09′E, Altitude 1,354 m above sea level), SA. The soil at the study site was classified as a Bainsvlei form according to the South African System (Soil Classification Working Group, 1991), equivalent to Chromic Stagnic Plinthic Cambisols (World Reference Base for Soil Resources (WRB), 2006). The soil was deep (>2,000 mm) with a fine sandy loam texture (Chimungu, 2009) and a clay, sand, and silt fraction of 8.5, 85, and 7%, respectively, at the start of the experiment (Table 1). The soil of the experimental site was moderately acidic with an average pH of 5.2, NH_4-N concentrations of 10.3 mg kg^{-1}, NO_3-N concentrations of 11.2 mg kg^{-1}, and available phosphorous concentrations of 7 mg kg^{-1} in the upper 300 mm horizons. The mean exchangeable base values for sodium, potassium, calcium, and magnesium were 22, 142, 336, and 100 mg kg^{-1}, respectively. The climate of the study area was categorized as semiarid with relatively low and erratic annual rainfall of 528 mm and mean annual minimum and maximum temperatures of 11.0 and 25.5°C, associated with high annual evaporative demand of 2,294 mm.

Meteorological variables were measured from an automatic weather station installed at the experimental farm. The automatic weather station consisted of a tipping bucket rain gauge, cup anemometer, wind vane, a pyrometer and combined temperature and humidity sensor. All meteorological data (rainfall, minimum and maximum temperatures, minimum and maximum relative humidity, wind speed and direction, and solar radiation) were recorded on a CR10X data logger (Campbell Scientific, USA) every 5 min, averaged over 1 h for storage and daily data were calculated by averaging the hourly data.

The land was prepared conventionally with a ripper, mold plow and disc. A ridge maker was used to make furrows and the basins were constructed using a basin maker against the N-S slope for the IRWH plots in December 2017 in an E-W direction. The runoff strips in the plots were raked to smooth the topsoil. Toward the end of January 2018, a smooth runoff slope was formed by hand in the runoff section. The IRWH plots were established with a 2:1 basin to runoff strip width ratio, which was based on previous field experience with crops in semiarid environments. Maize crops were planted in tramlines (1.1 m wide), which were adopted from the previous IRWH technique in the eastern Free State, SA (Botha et al., 2003). The no-till runoff zone was used in this experiment to integrate living mulch and to assess economic benefits.

Maize was planted at a constant population of 18,000 plants ha^{-1}. As a result, the experimental design for sunn hemp management was set up as a split-plot arranged in a randomized complete block design with three replications. To identify growth stages, the standard maize developmental stage system was used (from seedling emergence VE, to physiological maturity PM) (Ritchie et al., 1993). The experimental treatments (main plots) were sunn hemp at planting periods simultaneous

TABLE 1 Soil physical and chemical properties at the experimental site.

Chemical properties (0.00–0.35 m) (mg kg^{-1})		Diagnostic horizons				
		Depth (cm)	Color	Clay (%)	Bulk density (g cm^{-3})	pH (KCl)
NH_4-N	10.3	0.00–0.35	Red brown	8.5	1.66	5.2
NO_3-N	11.2	0.35–1.18	Red brown	14	1.68	5.1
P (Bray 1)	7.0	0.35–1.18	Brown	14	1.66	6.3
Na	22	1.18–1.80	Yellow orange	24	1.67	6.5
K	142	1.80–3.00	Yellow orange	24	1.68	6.6
Ca	336					
Mg	100					

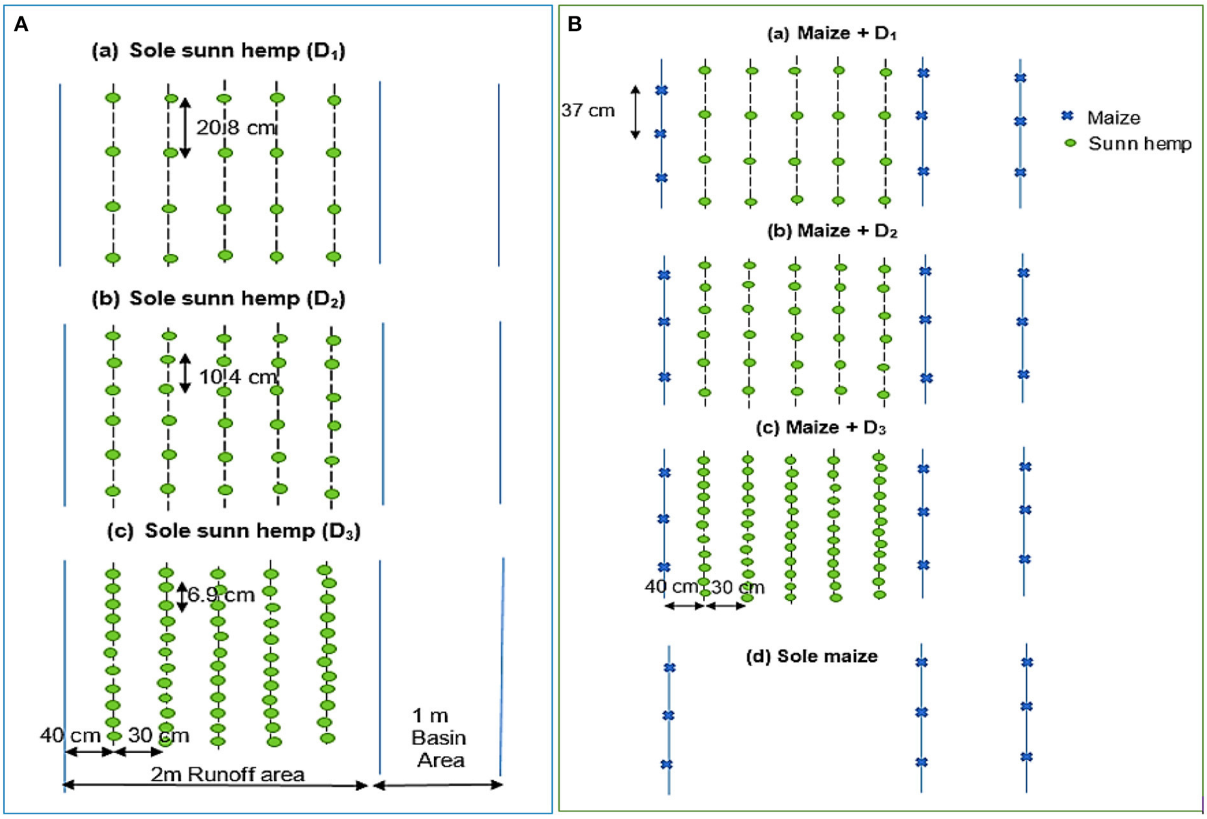

FIGURE 1
The spatial arrangement for living mulch cover crop planting density. **(A)** (a) Sole sunn hemp at D1 (16.1 plants m^{-2}); (b) sole sunn hemp at D2 (32.1 plants m^{-2}); (c) sole sunn hemp at D3 (48.1 plants m^{-2}). **(B)** (a) Maize + sunn hemp at D1 (16.1 plants m^{-2}); (b) maize + sunn hemp at D2 (32.1 plants m^{-2}); (c) maize + sunn hemp at D3 (48.1 plants m^{-2}); (d) sole maize.

with maize planting (P1), V15 maize growth stage (P2), and R1 maize growth stage (P3) assigned to the main plot. Sunn hemp was planted at three density levels of 16.1 plants m^{-2} (D1-low), 32.1 plants m^{-2} (D2-medium), and 48.1 plants m^{-2} (D3-high) in order to determine the optimum for intercropping. The sunn hemp subplots were planted in five rows, 90° to the runoff direction, with a 30 cm row spacing on the runoff strip of the IRWH technique. The intercrop components were sown in an additive series in both seasons (Connolly et al., 2001). Sole maize and sole sunn hemp were included, where sole sunn hemp was also planted at the respective three plant densities only at P1 treatment. The main plots were 180 m^2 (12 m width 15 m length), and the subplots were 60 m^2 (12 m width 5 m length). The schematic illustrations of the maize-based IRWH technique with sunn hemp management are depicted in Figure 1.

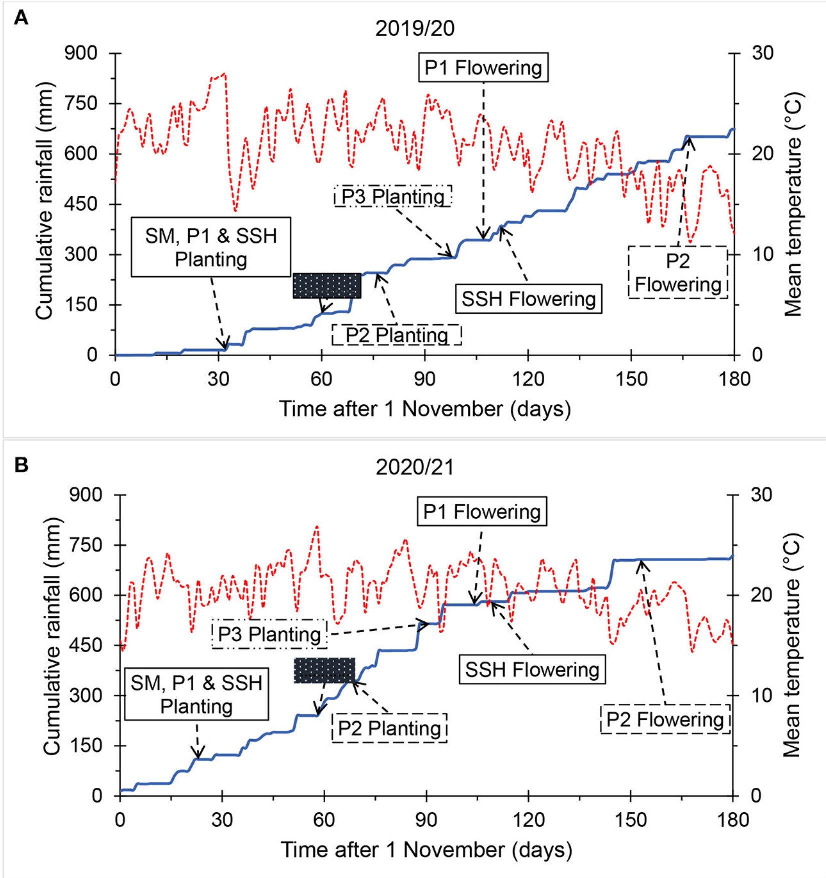

FIGURE 2
Cumulative daily rainfall, average daily temperature, and agronomic management practices during **(A)** 2019/20 and **(B)** 2020/2021 growing seasons. Red dotted line is the average daily air temperature, blue line is the cumulative rainfall since 1 November, shaded block is when in-field rainwater harvesting basins were modified. SM, sole maize; SSH, sole sunn hemp; P1, simultaneous sunn hemp intercropping; P2, intercropping sunn hemp at the early maize vegetative growth stage; P3, intercropping sunn hemp at the late maize vegetative growth stage.

Cropping system management

Planting of sole maize, sole sunn hemp, and P1 occurred on 3 December, 2019, and 23 November, 2020. The P2 sunn hemp was planted on 16 January, 2020 and 8 January, 2021, for each cropping season. P3 sunn hemp planting was done on 7 and 1 February for first and second growing seasons, respectively. Experimental crops were planted at relatively high densities and thinned to treatment planting densities 2 weeks after emergence. The growing season was sufficient for P1 and sole sunn hemp treatments to grow to maturity and produce seeds for sustainability in subsistence farming systems. However, growth measurements in all sunn hemp treatments were taken at 50% flowering and sunn hemp planted at P2 was terminated on 16 April, 2020 and 7 April, 2021. The sunn hemp planted at P3 grew slowly and did not reach flowering stage. Rainfed maize fertilizer applications were based on a potential yield of 5,000 kg ha^{-1} as determined by the Fertilizer Society of South Africa (FSSA) (2007). Maize (cv. Pioneer P2432R) and sunn hemp (cv. local) was fertilized with 200 kg ha^{-1} 2:3:2 (22) NPK equivalent to 13 kg N ha^{-1}, 19 kg P ha^{-1}, and 13 kg K ha^{-1}. No topdressing was applied on the sunn hemp. To meet the N requirements, a top dressing of 250 kg ha^{-1} LAN (28% N) (i.e., 70 kg ha^{-1} N) was applied as a split application to maize plots at 4 and 7 weeks after emergence. Weeds were manually controlled throughout the season, and spotted beetles were controlled with Dursban 480 EC as required. Crop harvesting was done by hand, and maize and sunn hemp stover was left in the field.

Data collection and calculations

Sunn hemp plant height and biomass

The plant height of sunn hemp during the flowering stage was determined by the average of 10 representative plants chosen

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from a 1 m^{-2} quadrant randomly placed in the plot. To calculate the biomass, all the plant samples harvested in the quadrant were oven-dried to a constant weight at 60°C for 72 h.

Growing degree days and leaf area index

The growing degree days for sunn hemp growth for each day from day after emergence (DAE) to flowering were calculated by averaging the maximum and minimum temperatures (°C) and subtracting 9.9°C as the base temperature (Qi et al., 1999). A linear AccuPAR LP-80 ceptometer was used to measure leaf area index (LAI) (Decagon Devices, Pullman, Washington, USA). The ceptometer collected data from 80 sensors embedded along with an 84 cm probe. At midday (12h00–14h00), LAI measurements were taken under clear skies. The LAI values were measured only at flowering of sunn hemp. At the soil surface, the line sensor was positioned perpendicular to the crop row.

Maize yield and harvest index

In this experiment, an area of 5 m^2 maize plants were manually harvested at maturity from the middle of each plot. Maize biomass was weighed soon after harvesting. The maize cobs were threshed using a hand-powered thresher. Maize grains were weighed and the mass was calculated at a water content of 12%. Harvest index (HI) was calculated as the ratio of grain to aboveground biomass.

Approach and estimation of economic performance

The economic performance of the sunn hemp was evaluated using net benefits, income equivalent ratio, replacement value of sunn hemp, and relative net return index. Non-labor costs such as fertilizers, seeds, and insecticides were used to calculate production costs. This was because household members in subsistence farming performed manual labor for field operations like planting, weeding, harvesting, and threshing (Botha et al., 2003). Revenues were calculated by multiplying the harvestable plot outputs with the local market price to obtain the amount of money earned from the sale of plot output (grain from maize and fodder from sunn hemp).

The net benefits (or profits) ha^{-1} were calculated as the difference between seasonal revenues and seasonal costs for each cropping system for maize-sunn hemp system (NB_{msh} in Equation 1). The net benefits for sunn hemp were calculated based on fodder yield at flowering, as seen in Equation (1) (Midega et al., 2014):

$$NB_{msh} = (P_m \times Y_{msh}) + \left(P_{shf} \times Y_{shf}\right) + (P_{shs} \times Y_{shs}) - C_{msh} \quad (1)$$

where seasonal maize yields from sunn hemp, sole maize, sunn hemp fodder yield, and sunn hemp seed yield are denoted by Y_{msh}, Y_{ms}, Y_{shf}, and Y_{shs}, respectively. P_m, P_{shf}, and P_{shs} are prices for maize grain, sunn hemp fodder, and sunn hemp seed (as the seed has different prices), respectively. C_{msh} and C_{ms} are the costs of producing sunn hemp living mulch and sole maize crop.

The income equivalent ratio is defined as the area required under pure stand to produce the same gross income under the same management level as that required under a sunn hemp system (Devasenapathy, 2008), as shown in Equations (2–4).

$$IER = \left(IER_m + IER_{sh}\right) \quad (2)$$

$$IER_m = \frac{Y_{mi} \times P_m}{Y_{ms} \times P_m} \quad (3)$$

$$IER_{sh} = \frac{Y_{shi} \times P_{sh}}{Y_{shs} \times P_{sh}} \quad (4)$$

Where IER is the income equivalent ratio, IER_m and IER_{sh} represent the partial IER of maize and sunn hemp, respectively. Y_{mi} and Y_{ms} represent the yields of maize in sunn hemp and pure stand (sole), respectively. Y_{shi} and Y_{shs} are sunn hemp yields in intercropping and pure stand, respectively. P_m and P_{sh} are the prices for maize grain and sunn hemp (or Lucerne) fodder or seed, respectively.

The replacement value of a sunn hemp living mulch system proposed by Moseley (1994) and Singh et al. (2015) was used to account for the variable costs associated with the sunn hemp enterprise in relation to the economic value of the cultivated crop (Equation 5).

$$RVsh = \frac{(Y_{mi} \times P_m) + \left(Y_{shi} \times P_{sh}\right)}{Y_{ms} \times P_m - C_{ms}} \quad (5)$$

where C_{ms} is the variable cost of maize (the main crop) in a pure stand. The relative net return index was calculated following a formula (Equation 6) suggested by Mead and Riley (1981).

$$RNRI = \frac{\left[\left(Y_{mi} \times P_m + Y_{sh} \times P_{sh} \pm D_{msh}\right)\right]}{Y_{ms} \times P_m} \quad (6)$$

Where $RNRI$ is the relative net return index, D_{msh} is the difference in the cost of cultivation (variable cost) between maize-sunn hemp system and that of pure maize stand. A RNRI value >1 is preferred because it indicates that sunn hemp gives higher returns compared to pure stand.

Statistical analysis

The JMP Pro 14 statistical software for Windows was used for all analyses (SAS Institute, Inc., North Carolina, USA, 2010). Treatments were considered as maize plots with varying planting periods and densities of sunn hemp for one-way analysis of variance (ANOVA) to test the statistical significance of treatments in comparison with the sole maize between growing seasons. However, for testing the planting period and density

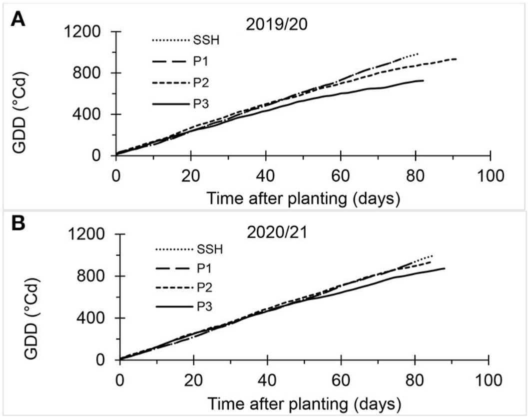

FIGURE 3
The growing degree days (GDD) (°Cd) for sunn hemp living mulch management practices during **(A)** 2019/2020 and **(B)** 2020/2021 growing seasons (SSH, sole sunn hemp; P1, simultaneous sunn hemp and maize planting; P2, sunn hemp planted at the V15 maize growth stage; P3, sunn hemp planted at R1 maize growth stage).

TABLE 2 Sunn hemp plant height as influenced by planting period (P) and growing season (S) under the in-field rainwater harvesting technique in the central semiarid area of the Free State Province, South Africa.

	Plant height (cm)		
	Growing season		
Planting period (P)	**2019/20**	**2020/21**	**Mean**
SSH	143.6[c]	116.1[e]	129.8[b]
P1	125.2[d]	116.9[de]	121.1[b]
P2	163.0[b]	200.6[a]	181.8[a]
P3	100.0[f]	35.6[g]	67.8[c]
Mean	132.9[a]	117.3[b]	
p-value	<0.001**		
$LSD_{(0.05)}$	8.9		
CV (%)	7.5		

SSH, sole sunn hemp; P1, simultaneous sunn hemp and maize planting; P2, sunn hemp planted at the V15 maize growth stage; P3, sunn hemp planted at R1 maize growth stage. Means followed by the same letter in a column for each treatment are not significantly different according to LSD (0.05). ** Significant at $p < 0.05$, 0.001 probability level, CV is Covariance of sample.

effects, as well as their two way interactions on sunn hemp growth and biomass, the variables were fitted as fixed factors. When the significance of the treatment on the F-statistic is mentioned, it refers to a comparison using the least significant differences (LSD) at the 0.05 probability level.

Results

Weather conditions and growing degree days

Treatment differences were attributed to varying weather patterns across the experimental seasons. Rainfall distribution, average temperature and timing of sunn hemp planting for the 2019/20 and 2020/21 growing seasons are presented in Figure 2. The primary weather variable, rainfall, influenced sunn hemp living mulch management practices in both seasons. Therefore, because of the rainfall variations (Figure 2A), the maize and sunn hemp planting dates differed between the two experimental years, with early planting occurring in the first growing season (2019/20). The total amount of rainfall during the growing season was 673.7 mm, evenly distributed throughout the season, with 16.1, 24.2, 18.9, 20.1, and 18.4% rainfall in December, January, February, March, and April, respectively. Plant emergence was slow and poor in all treatments because of the small amount (2.3%) of rainfall received at P1 planting. The continuous rainfall distribution throughout the following months was favorable for P2 and P3 treatments during 2019/20, as shown in Figure 2A.

Due to the good early rainfall distribution during the 2020/21 season, sole maize, sole sunn hemp and P1 treatments were planted in late November 2020, as 17% of total seasonal rainfall had already been received (Figure 2B). However, it was a disadvantage for establishing and growing P1 and sole sunn hemp treatments because sunn hemp is prone to fungal and bacterial diseases under wet conditions. Rainfall peaked in January (32.5% of total seasonal rainfall) but declined from February to April 2021. April received only 2% of total seasonal rainfall, causing poor and delayed germination in the P3 treatment. Overall, the second cropping season (2020/21) was the wettest, with 718.8 mm of seasonal rainfall received.

Sunn hemp flowering occurred at different days after emergence (DAE) during the respective 2019/20 and 2020/21 growing seasons as follows: sole sunn hemp (76 and 82 DAE), P1 (71 and 77 DAE), and P2 (88 and 82 DAE) (Figures 2A,B). The growing degree days (°Cd) to reach flowering varied depending on the sunn hemp planting period, cropping system and season (Figures 3A,B). During the 2019/20 and 2020/21 growing seasons, the sole sunn hemp treatment required 988 and 995°Cd to grow and reach the flowering stage, respectively. During the 2019/20 and 2020/21 growing seasons, P1 treatments required 934 and 936°Cd, while P2 treatments required 933 and 941°Cd to grow and reach flowering stage, respectively. This demonstrated that intercropping sunn hemp reduced the growing degree days required for flowering, resulting in earlier flowering when compared to sole sunn hemp control treatments. Sunn hemp living mulch planted at P3 did not reach flowering stage because it is a photoperiod sensitive crop.

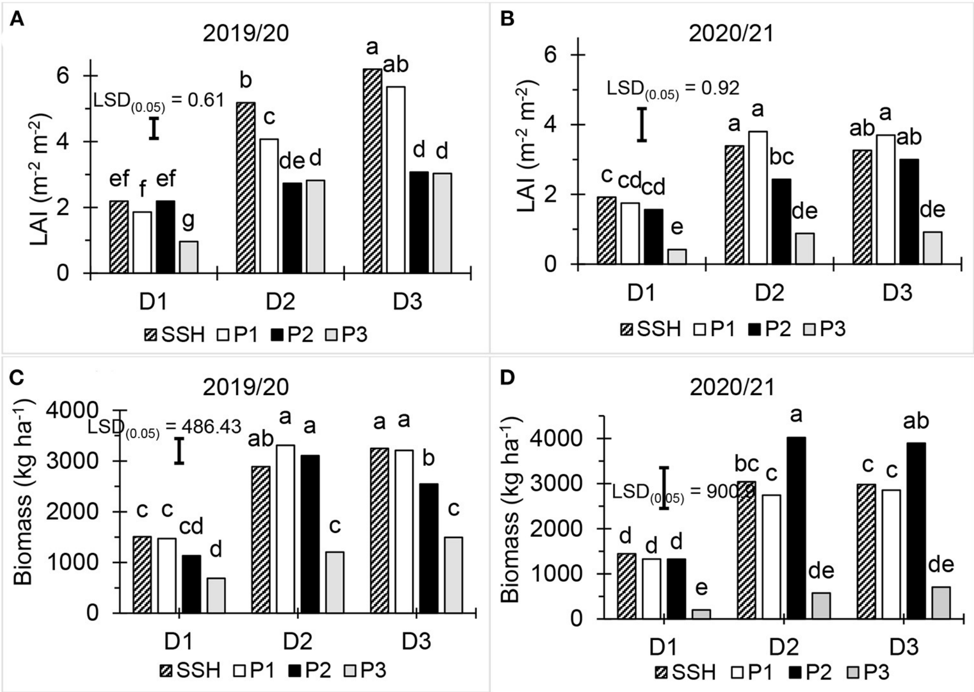

FIGURE 4
Planting period and density effects on sunn hemp under the in-field rainwater harvesting technique in the central semiarid area of the Free State Province, South Africa: **(A)** leaf area index ($m^{-2}m^{-2}$) during 2019/2020 growing season; **(B)** leaf area index ($m^{-2}m^{-2}$) during 2020/21 growing season; **(C)** biomass (kg ha^{-1}) during 2019/20 growing season; **(D)** biomass (kg ha^{-1}) during 2020/21 growing season (SSH, sole sunn hemp; P1, simultaneous sunn hemp and maize planting; P2, sunn hemp planted at the V15 maize growth stage; P3, sunn hemp planted at R1 maize growth stage; D1-low, 16.1 plants m^{-2}; D2-medium, 32.1 plants m^{-2}; D3-high, 48.1 plants m^{-2}). Different letters on the bars indicate statistical significance.

Management effects on sunn hemp growth and yield

Plant height

The sunn hemp plant height of 200.6 cm obtained with the P2 treatment during the second growing season (2020/21) was significantly different from the 163 cm obtained with the same treatment during the first growing season (2019/20) (Table 2). Sunn hemp growth in the 2019/20 growing season, on the other hand, achieved significantly higher plant heights in sole sunn hemp and P3 when compared to the 2020/21 growing season. The highest sunn hemp plant height values obtained with P2 in both growing seasons demonstrated the competitive response of sunn hemp establishment into standing maize, which is an important factor for farmers to consider in adoption decisions.

Leaf area index

There was consistent significant ($p < 0.05$) increases in LAI values with plant density in the sole sunn hemp (D1, 2.19 $m^{-2}m^{-2}$; < D2, 5.18 $m^{-2}m^{-2}$; < D3, 6.20 $m^{-2}m^{-2}$) and P1 (D1, 1.86 $m^{-2}m^{-2}$; < D2, 4.07 $m^{-2}m^{-2}$; < D3, 5.66 $m^{-2}m^{-2}$) treatments during the 2019/20 cropping season (Figure 4A). Management at P1 with D3 planting density had comparable significant ($p < 0.05$) LAI values to D2 and D3 values in sole sunn hemp in the same cropping season. The overall results revealed a linear increase in sunn hemp leaf area index with increasing plant density per area (Figure 5B). However, comparable LAI values were obtained during the 2020/21 growing season with P2 and P3 management at D2 and D3 planting densities (Figure 4B). The LAI is an important indicator of sunn hemp morphological plasticity, which can be exploited by managing plant density. The interplay of planting period and density is one practice that farmers can use to improve the benefits of sunn hemp living mulch, as reflected in LAI, which represents canopy shading.

Yield

The biomass yield differed significantly ($p < 0.05$) between planting period treatments when planted at D3 during the

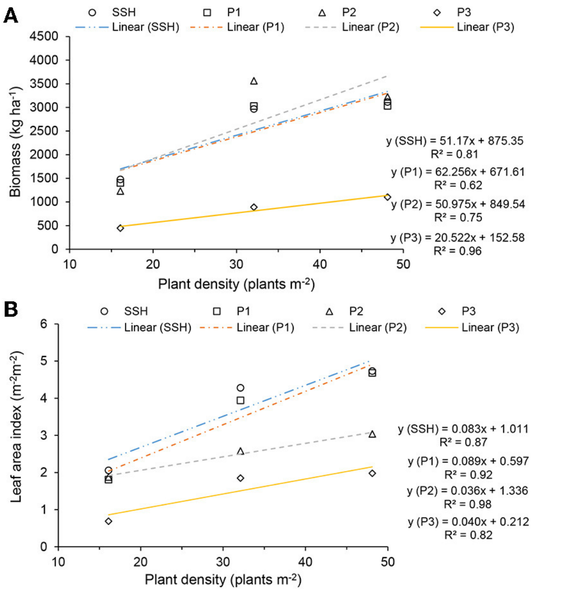

FIGURE 5
Sunn hemp biomass (kg ha^{-1}) **(A)** and leaf area index ($m^{-2}m^{-2}$) **(B)** as a function of plant density per area (SSH, sole sunn hemp; P1, simultaneous sunn hemp and maize planting; P2, sunn hemp planted at the V15 maize growth stage; P3, sunn hemp planted at R1 maize growth stage).

2019/20 growing season (Figure 4C). The differences were: P1D3, 3,209 kg ha^{-1}, < P2D3, 2,546 kg ha^{-1}, and < P3D3, 1495.3 kg ha^{-1}, in that order. The P3 treatment produced significantly less biomass than the sole sunn hemp and other treatments at all plant densities. However, the biomass yield obtained with P3 at D2 and D3 did not differ statistically from that obtained with sole sunn hemp, P1, and P2 at D1. The P3 effect was the same during 2020/21 growing season (Figure 4D). Sunn hemp planting with P2 at D2 and D3 during the 2020/21 growing season performed significantly ($p < 0.05$) better when compared to sole sunn hemp and other planting period treatments. The study's findings revealed a linear increase in sunn hemp biomass (Figure 5A) with increasing plant density per area. The interplay of sunn hemp living mulch planting period and density management with the growing season emphasizes the importance of adjusting them based on the forecasted weather conditions for the growing season. Allowing the sole sunn hemp and P1 treatments growth to maturity (see Appendix A1) showed that highest biomass yields were obtained at D2 (sole sunn hemp: 10234.7 kg ha^{-1} and P1: 9355.5 kg ha^{-1}). The sole sunn hemp treatment at D2 (1029.7 kg ha^{-1}), D3 (917.8 kg ha^{-1}) and for P1 at D2 (911.3 kg ha^{-1}) had the highest seed yield.

Effects of sunn hemp management on maize yield

Planting period

Sunn hemp planting period had significant ($p < 0.001$) effects on maize biomass showing that P1 and P2 treatments improved maize biomass productivity in both growing seasons (Table 3a). During the 2019/2020 growing season, P1 (6292.8 kg ha^{-1}), and P2 (6096.9 kg ha^{-1}) treatments were the highest compared to P3 (4996.4 kg ha^{-1}) and sole maize (5411.7 kg ha^{-1}). Sunn hemp planting at P3 resulted in significant ($p < 0.014$) maize grain yield reduction. The maize grain yields were P3 (2775.2 kg ha^{-1}), sole maize (3263.8 kg ha^{-1}), P2 (3281.9 kg ha^{-1}), and P1 (3287.8 kg ha^{-1}). Planting sunn hemp with P1 is an important management factor to for farmers to consider when aiming for higher biomass and grain yields. The 2019/20 growing season resulted in the highest grain yield of 3395.6 kg ha^{-1} compared to 2908.7 kg ha^{-1} in 2020/21 growing season. The harvest index significantly differed between the two growing seasons with the highest (0.60) obtained in 2019/20 (Table 3a).

Plant density

Sunn hemp plant density resulted in significant ($p < 0.005$) effects on maize grain yield where at D2, the highest grain yield of 3305.0 kg ha^{-1} was not different from sole maize (3263.8 kg ha^{-1}) and D1 (3183.2 kg ha^{-1}) (Table 3b). The lowest grain yield was obtained with D3 (2856.7 kg ha^{-1}). Sunn hemp plant density had significant ($p < 0.005$) effects on harvest index showing that 2019/20 growing season resulted in high values of 0.65 and 0.62 obtained in sole maize and D2, respectively, and were not significantly different in D3 (0.58) (Table 3b). Therefore, D2 was the optimum sunn hemp plant density to consider as maize grain yield was higher compared to sole maize control. This is an advantage for obtaining living mulch benefits with less sunn hemp seed and without reducing maize grain yield. The overall results showed a linear decrease in biomass and grain yield with increase in sunn hemp plant density per area (Figures 6A,B).

Interactive management effects on economic benefits

Sunn hemp planting period yielded high net benefits for P1 (USD 404.07) and P2 (USD 408.31) (Table 4). P3 had the lowest profits due to the low biomass of sunn hemp and the yield reduction effect. However, D2 was the best sunn hemp planting density, with a net benefit advantage of USD 407.96, indicating that farmers should consider seed saving. Furthermore, when mature P1 sunn hemp seeds were harvested, D2 (see Appendix A2) provided the highest profits. Their impact exhibited a similar pattern to net benefits for the replacement

TABLE 3 Effects of sunn hemp living mulch planting period (P) and density (D) on maize biomass, grain yield, and harvest index under the in-field rainwater harvesting technique in the central semiarid area of the Free State Province, South Africa.

	Biomass (kg ha^{-1})			Grain yield (kg ha^{-1})			Harvest index		
	Growing season			Growing season			Growing season		
	2019/20	2020/21	Mean	2019/20	2020/21	Mean	2019/20	2020/21	Mean
Planting period (P)									
(a)									
SM	5411.67^{d}	5163.14^{de}	5287.40^{b}	3483.33^{ab}	3044.23^{bc}	3263.78^{a}	0.65^{a}	0.59^{ab}	0.62^{a}
P1	6292.78^{a}	5960.52^{bc}	6126.65^{a}	3477.78^{ab}	3097.86^{bc}	3287.82^{a}	0.55^{abc}	0.52^{bc}	0.54^{b}
P2	6096.94^{ab}	5815.76^{c}	5956.35^{a}	3606.67^{a}	2957.06^{cd}	3281.86^{a}	0.59^{ab}	0.51^{bc}	0.55^{ab}
P3	4996.39^{e}	5210.79^{de}	5103.59^{b}	3014.44^{bc}	2535.94^{d}	2775.19^{b}	0.60^{ab}	0.49^{c}	0.55^{ab}
Mean	5699.44^{a}	5537.55^{b}		3395.56^{a}	2908.77^{b}		0.60^{a}	0.53^{b}	
p-value	0.023*			0.845			0.642		
LSD$_{(0.05)}$	260.05			–			–		
CV (%)	2.64			8.64			10.16		
Plant density (D)									
(b)									
SM	5411.67^{ab}	5163.14^{b}	5287.40^{a}	3483.33^{a}	3044.23^{a}	3263.78^{a}	0.65^{a}	0.59^{ab}	0.62^{a}
D1	5932.22^{a}	5611.51^{ab}	5771.87^{a}	3282.78^{a}	3083.57^{a}	3183.18^{a}	0.56^{b}	0.55^{b}	0.55^{b}
D2	5773.61^{ab}	5678.34^{ab}	5725.98^{a}	3540.83^{a}	3069.26^{a}	3305.04^{a}	0.62^{a}	0.54^{b}	0.58^{ab}
D3	5680.28^{ab}	5697.2^{ab}	5688.75^{a}	3275.28^{a}	2438.03^{b}	2856.65^{b}	0.58^{ab}	0.43^{c}	0.50^{c}
Mean	5699.44^{a}	5537.55^{a}		3395.56^{a}	2908.77^{b}		0.60^{a}	0.53^{b}	
p-value	0.816			0.104			0.005**		
LSD$_{(0.05)}$	–			–			0.09		
CV (%)	9.68			12.09			10.04		

SM, sole maize; P1, simultaneous sunn hemp and maize planting; P2, sunn hemp planted at the V15 maize growth stage; P3, sunn hemp planted at R1 maize growth stage; D1-low, 16.1 plants m^{-2}; D2-medium, 32.1 plants m^{-2}; D3-high, 48.1 plants m^{-2}. Means followed by the same letter in a column for each treatment are not significantly different according to LSD (0.05). *, ** Significant at $p < 0.05$, 0.001 probability level, CV is Covariance of sample.

value of sunn hemp (RV_{sh}) and relative net return index. The sunn hemp planting period effect for RV_{sh} was P1 (1.09) and P2 (1.12), and for relative net return index P1 (1.20) and P2 (1.21). At P1 and P2 planting periods, the RV_{sh} was more significant than one, indicating that using sunn hemp as living mulch was a highly beneficial management practice for farmers using IRWH technique. However, farmers should avoid using the P3 planting period because a relative net return index value <1 indicated that sunn hemp in sole stand yielded higher returns. Although the planting density effect was increased in both RV_{sh} and RNRI at D2, an RV_{sh} value of 0.95 at D3 indicated that intercropping that sole stand resulted in a loss. When P1 was harvested at maturity, the RV_{sh} and RNRI values obtained with D1 (see Appendix A2) were more significant than one, but they were the lowest compared to D2 and D3.

Sunn hemp planting period and plant density had a significant ($p < 0.05$) effect on the maize income equivalent ratio (IER_m) (Table 4). The planting period resulted in a significantly lower IER_m (0.86) at P3 than at P1 and P2 (1.02). Plant density also reduced IER_m at D3 (0.88) vs. D1 (0.99) and D2 (1.02). The values obtained at P3 and D3 were >0.5, indicating that the benefits of intercropping in improving economic returns were realized. However, planting period at P3 (0.32) resulted in a value <0.5 for sunn hemp IER_{sh}. The total income equivalent ratio for all planting period treatments P1 (2.02), P2 (2.09), and P3 (1.18) was greater than unity, but the P3 value was significantly lower.

Discussion

The goal of this study was to determine how planting periods (P) and densities (D) of sunn hemp living mulch affected growth parameters, biomass, maize grain yields, and economic returns in an IRWH maize-based system. Comprehensive living mulch performance and impact on main crop is required for providing recommendations for smallholder farmers in rainfed semiarid areas to sustainably integrate living mulches in maize monocropping systems.

Sunn hemp performance

The impacts of living mulch planting period on growth and biomass are well-known. Generally, earlier planting of

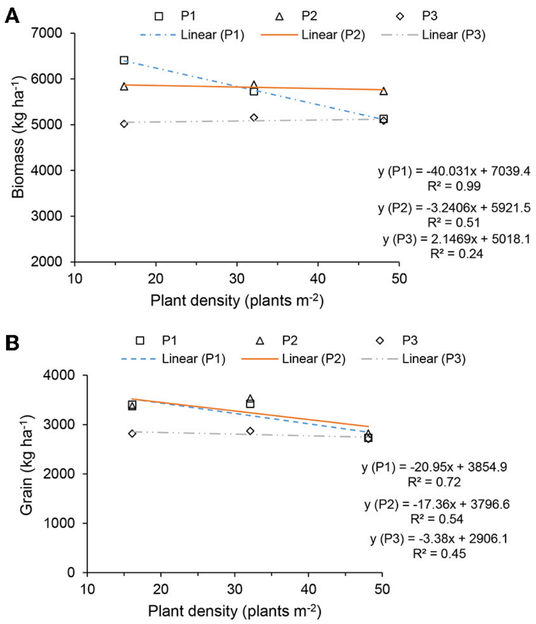

FIGURE 6
Maize biomass **(A)** and grain yield (kg ha^{-1}) **(B)** as a function of plant density per area (P1, simultaneous sunn hemp and maize planting; P2, sunn hemp planted at the V15 maize growth stage; P3, sunn hemp planted at R1 maize growth stage).

living mulch into the main crop will result in early ground cover and higher biomass relative to late planting. However, improved growth of early planted living mulches is attributed to the long growing season exposure of temperature and rainfall distribution (Wilson et al., 2013; Curran et al., 2018). This notion, however, is dependent on the living mulch species. In this study, 17% of rainfall was received at the start of the 2020/21 growing season (Figure 2B) but early sunn hemp establishment and growth at P1 was slow and some leaf necrosis was observed (data not shown). However, the plants recovered and densities were not compromised because treatments were planted at relatively high densities. High rainfall limits the growth of sunn hemp, which is susceptible to waterlogging soil conditions and becomes vulnerable to fungal and bacterial diseases (Baligar and Fageria, 2007). In relation to this study, establishment of sunn hemp was particularly challenging under the IRWH technique especially when planting with high rainfall amounts and subsequent intolerance to water logging conditions (Subrahmaniyan et al., 2021). Other research has shown that late planting of living mulch into an established main maize crop is a recommended management practice for allowing the living mulch to utilize late season rainfall and soil moisture (Mirsky et al., 2011; Belfry and Van Eerd, 2016; Mhlanga et al., 2016).

In this study, the late planting of sunn hemp into standing maize at the R1 maize growth stage (P3) resulted in significantly low biomass (Figures 4C,D). Although rainfall was fairly distributed during 2019/20 compared to 2020/21 growing season there were no significant differences observed in biomass with P3. This contradicts the notion of less rainfall amount and distribution availability associated with late planting of living mulches (Wilson et al., 2013). Therefore, there are other factors involved in determining the biomass of sunn hemp. Simultaneously planting with maize (P1) and V15 maize growth stage (P2) were the best planting periods for obtaining high biomass. This observation was likely due to well-distributed rainfall, less maize competition for water or sunlight, and enough number of growing degree days required for sufficient biomass production (Lawson et al., 2015). Therefore, in this study competition for sunlight with main crop and limited number of growing degree days could have been the main factors that limited P3 biomass production. Figures 2A,B showed that the mean temperatures dropped in both growing seasons when the P3 living mulches were planted. Sunn hemp development and biomass production is influenced by the interaction of photoperiod and temperature, as well as planting period (de Oliveira Miranda et al., 2020; Subrahmaniyan et al., 2021). Dropping temperatures observed at late planting in the growing season and the association with shortening day lengths could have been the main causes of a decrease in biomass production in P3. As a result, seeding sunn hemp early in the summer wet season yielded significantly more than later sowing. In addition, the growing season had a direct effect on the vegetative growth and development of sunn hemp.

Information on how sunn hemp plant density influences its growth and biomass is vital for optimizing living mulch benefits (de Oliveira Miranda et al., 2020). In this study, the evaluation of sunn hemp at three plant densities showed that D2 (32.1 plants m^{-2}) and D3 (48.1 plants m^{-2}) resulted in the highest biomass accumulation when compared to D1 (16.1 plants m^{-2}) (Figures 4C,D). Sunn hemp biomass production is plant density responsive, meaning that it increases when planted at higher plant densities relative to low plant densities (de Oliveira Miranda et al., 2020). This study found that biomass attained with P1 (simultaneous planting sunn hemp with maize) and P2 (planting at the V15 maize growth stage) at D2 (32.1 plants m^{-2}) and D3 (48.1 plants m^{-2}) were higher than those in D1 (16.1 plants m^{-2}). It was evident that low density planting of sunn hemp resulted in low biomass regardless of the planting time. Thus, when considering increasing biomass production by increasing plant density, it is critical to consider seed availability and cost. Farmers may be discouraged from using higher sunn hemp plant densities in smallholder and subsistence farming due to the low biomass return compared to the higher seed cost when increasing plant density at D2 and D3. As a result, farmers must produce their own seed in order to continue to practice sustainable agriculture. However, the LAI values were

TABLE 4 Effects on sunn hemp management on net benefits (NB), replacement value of sun hemp (RV_{sh}), relative net return index (RNRI), maize income equivalent ratio (IER_m), sunn hemp income equivalent ratio (IER_{sh}), and income equivalent ratio (IER) under in-field rainwater harvesting technique in the central semiarid area of the Free State Province, South Africa.

		Plant density (D)					Plant density (D)			
	Planting period (P)	**D1**	**D2**	**D3**	**Mean**		**D1**	**D2**	**D3**	**Mean**
	P1	395.43^{ab}	480.69^{a}	336.08^{bcd}	404.07^{a}		1.06^{ab}	1.11^{a}	0.89^{c}	1.02^{a}
NB	P2	390.51^{ab}	477.44^{a}	356.96^{bc}	408.31^{a}	IER_m	1.05^{ab}	1.08^{a}	0.92^{bc}	1.02^{a}
	P3	227.56^{e}	265.75^{cde}	238.26^{de}	243.86^{b}		0.85^{c}	0.88^{c}	0.83^{c}	0.86^{b}
	Mean	337.83^{b}	407.96^{a}	310.44^{b}			0.99^{a}	1.02^{a}	0.88^{b}	
	p-value		0.534					0.539		
	$LSD_{(0.05)}$		–					–		
	CV (%)		24.95					12.73		
	P1	1.12^{bc}	1.19^{ab}	0.97^{de}	1.09^{a}		0.99^{ab}	1.04^{ab}	0.98^{ab}	1.00^{a}
RV_{sh}	P2	1.10^{bc}	1.25^{a}	1.01^{cd}	1.12^{a}	IER_{sh}	0.91^{b}	1.26^{a}	1.05^{ab}	1.07^{a}
	P3	0.89^{de}	0.92^{de}	0.88^{e}	0.90^{b}		0.31^{c}	0.31^{c}	0.34^{c}	0.32^{b}
	Mean	1.04^{b}	1.12^{a}	0.95^{c}			0.74^{a}	0.87^{a}	0.79^{a}	
	p-value		0.153					0.559		
	$LSD_{(0.05)}$		–					–		
	CV (%)		9.89					34.00		
	P1	1.19^{ab}	1.31^{a}	1.10^{bc}	1.20^{a}		2.04^{ab}	2.15^{ab}	1.87^{b}	2.02^{a}
RNRI	P2	1.18^{ab}	1.30^{a}	1.13^{bc}	1.21^{a}	IER	1.96^{b}	2.33^{a}	1.97^{b}	2.09^{a}
	P3	0.95^{d}	1.00^{cd}	0.95^{d}	0.96^{b}		1.16^{c}	1.20^{c}	1.78^{c}	1.18^{b}
	Mean	1.11^{b}	1.20^{a}	1.06^{b}			1.72^{ab}	1.89^{a}	1.67^{b}	
	p-value		0.591					0.457		
	$LSD_{(0.05)}$		–					–		
	CV (%)		11.28					16.14		

P1, simultaneous sunn hemp and maize planting; P2, sunn hemp planted at the V15 maize growth stage; P3, sunn hemp planted at R1 maize growth stage; D1-low, 16.1 plants m^{-2}; D2-medium, 32.1 plants m^{-2}; D3-high, 48.1 plants m^{-2}. Means followed by the same letter in a column for each treatment are not significantly different according to LSD (0.05). CV is Covariance of sample.

similar for the various planting periods and densities between both growing seasons (Figures 4A,B). These results show that sunn hemp can compensate for low planting densities through intraspecific mechanisms of competition, such as branching and higher morphological plasticity, i.e., modified growth habits to occupy more space (Morris et al., 2015). According to Morris et al. (2015), planting sunn hemp at low density resulted in six branches, more than the three produced by high-density planting. Although increasing plant populations have traditionally been proposed to increase cover cropping benefits (Mosjidis and Wehtje, 2011), this explains the similarities in LAI values in this study. Such information is particularly relevant to the organic farming system, where weed management is expensive and the farmer has limited options because of the non-inclusivity of chemical management. When sunn hemp was planted at low densities ranging from 20 to 50 plants m^{-2}, Mosjidis and Wehtje (2011) discovered no significant differences in biomass yields and substantial reductions in weed biomass. Sunn hemp living mulch could greatly benefit from maize production systems under IRWH technique because weed management is a pressing issue, especially for financially limited subsistence farmers.

Maize performance

The fundamental principle of a living mulch is to provide vegetative cover during the main crop growing season on soil surfaces that would otherwise be bare (Mzezewa et al., 2011). However, competition for resources with main crop is one of the biggest and most obvious concerns and limitations of living mulches, which may result in main crop yield reductions (Jeranyama et al., 2000). This is a particular problem in areas where water is a limiting resource, or where production is dependent on rainfall, as living mulches will utilize water that could otherwise have been utilized by the main crop (Batista De Morais et al., 2020). This study (Table 3a) showed that planting the sunn hemp living mulch earlier at P1 (simultaneous planting sunn hemp with maize) and P2 (planting at the V15 maize growth stage) could boost maize production with the IRWH technique. Sunn hemp has a vigorous early growth that is associated with high water use, so introducing it earlier in the maize growing season is a subtle management approach, which allows it to use water when the maize requires less water. Therefore, the earlier establishment of the sunn hemp living mulch resulted in a complementary use of water resources, which could have had an effect on soil moisture conservation through canopy shading later in the growing season when maize water demand was at a peak.

Maize water demands are critical at the flowering and grain filling stages and water competition during those periods can result in maize grain yield penalty (Batista De Morais et al., 2020). This is important in explaining the grain yield reductions observed in this study when the sunn hemp living mulch was planted at the R1 maize growth stage (P3). In 2019/20, the maize grain yield obtained with P3 was not significantly different from P1 (simultaneous planting of sunn hemp and maize) or sole maize (Table 3). Furthermore, P3 maize grain yield did not differ significantly from P2 maize grain yield during the 2020/21 growing season (planting at the V15 maize growth stage). Excessive nutrient competition during critical growth stages for component crops with P3 (R1 maize growth stage), particularly for soil mineral N, may have resulted in maize grain yield reduction, as N is a critical macronutrient that determines yield potential. However, if there had been a dry season, water competition effects on maize grain yield reduction could have been observed with P1 (simultaneous planting of sunn hemp and maize) and P2 (planting at the V15 maize growth stage). Similar findings on main crop grain yield reduction were observed in Brazil when maize was intercropped with living mulches including palisade grass (*Urochloa brizantha* cv. Marandu), pigeon pea (*Cajanus cajan* cv. Iapar 43), and sunn hemp (Batista De Morais et al., 2020). However, in another study, cover crops did not affect maize biomass or grain yields in SA's warm temperate zone when they were relay planted at the maize vegetative growth stage under conventional tillage (Murungu et al., 2011). Relay planting of cover crops at the maize establishment stage on sandy, loamy soil in Zimbabwe did not reduce maize grain yields, whether fertilized with 60 kg N^{-1} or not (Jeranyama et al., 2000). However, due to differences in growing conditions, planting time, and species grown, there can be several positive, neutral, negative or mixed responses of living mulch on the main crop (Mohammadi and Ghobadi, 2010; Belfry and Van Eerd, 2016). Ruffatti et al. (2019), for example, found a 7–22% reduction in maize yield when using a rye and radish blend as a living mulch. In contrast, Belfry and Van Eerd (2016) observed no yield reduction when intercropping 17 different cover crop species along with varying mixes into maize at the V4–V6 stage. Balkcom and Reeves (2005) obtained maize grain yield improvement of 22% in a maize cropping sequence following sunn hemp. The findings indicated that growing maize with living mulch is a management tool to provide ecosystem benefits, but its success and impact on the main crop depends on the growing environment and specific management activities.

Economic performance

The effect of sunn hemp living mulch on the economic status in a maize-based cropping system was investigated using economic benefit analysis. Cover cropping is rarely evaluated in terms of the purported economic impacts of its use in a cropping system. However, studies report negative effects, such as crop yield reductions caused by cover crop use (Ruffatti et al., 2019). Claims of massive economic gain are common with cover crops in cropping systems as well (Schomberg et al., 2014). The importance of cover crops is to increase productivity by improving soil fertility, to reduce the build-up of endemic diseases and pests associated with monoculture, and to reduce production costs by reducing or avoiding the use of external inputs, particularly fertilizers and pesticides (Baraibar et al., 2018). Cover crops have, however, costs that may limit their use. These include the cost of additional seed, the time required to manage an additional crop, which may necessitate changes to current cropping plans, and the cost of an additional herbicide or increased tillage to kill the cover crop in order to plant the cash crop (Cai et al., 2019).

The lack of immediate economic return and the area that must be occupied by living mulches are among the main causes for the lack of adoption. As a result, selecting living mulch species with immediate economic returns, such as the sale of forage or seeds (Schomberg et al., 2014), is the first appropriate management to improve the economic returns of crop-livestock smallholder farmers. A comparison of net benefits between sunn hemp planting period and density treatments was made based on the value of the harvested sunn hemp forage at flowering or seed harvest at maturity. We assumed that sunn hemp seed harvest was an opportunity for smallholder farmers to ensure continued adoption. In this scenario, P1 (simultaneous planting sunn hemp with maize) offers an economic advantage over termination of sunn hemp at flowering, since the seed value of sunn hemp would be greater and forage cost of sunn hemp would be less. Therefore, at forage stage, sunn hemp planted at P1 yielded higher net benefits than when planted at P2 (planting at the V15 maize growth stage) and P3 (planting at the R1 maize growth stage) (Table 4). At maturity, sunn hemp planted at P1 yielded higher net benefits than when planted at D2 (medium density: 32.1 plants m^{-2}) and D3 (high density: 48.1 plants m^{-2}) (Appendix A2). However, the high net benefits of P1 (simultaneous planting sunn hemp with maize) both at flowering and maturity were greater at D2 (32.1 plants m^{-2}) than at D3 (48.1 plants m^{-2}), and this was associated with higher seed yields at medium density. The effect on net benefits was also similar for replacement value, relative net return index, and income equivalent ratio.

The income equivalent ratio (IER) may vary yearly due to fluctuating market prices for inputs and crop outputs. Because it affects market demand and supply dynamics, climate change directly impacts price volatility. The IER is conceptually similar to the LER, with the difference that yield is measured in terms of net income rather than plant productivity. The IER (Devasenapathy, 2008), simply states that a (i) value of one indicates that the income of the sole cropping system and the intercropping system is equivalent, (ii) a value >1 indicates that the intercropping system provides a positive income benefit, and (iii) a value <1 indicates that the sole cropping system provides a higher income than the intercropping system. In this regard, results of partial IER for maize (IER_m) obtained for P3, which was <1 but above 0.5, means that there was an economic advantage for both component crops in gross income (Table 4). However, partial IER_{sh} obtained with P3 of <0.5 showed an income loss with sunn hemp integration. This is because crop yield, price, and inputs determine gross income even when agronomic responses are consistent.

Conclusion

The results show that late planting of sunn hemp living mulch during R1 maize growth stage had a negative effect on maize grain yield. However, planting of sunn hemp during the V15 maize growth stage was appropriate for incorporation with maize production in semiarid areas. This was due to the good amount of sunn hemp biomass produced without reducing maize yield relative to maize monocrop. The economic analyses indicated that the highest economic productivity in terms of net benefits, replacement value, and relative net return index was achieved with simultaneous sunn hemp planting with maize (P1) at the planting densities of 32.1 plants m^{-2} (D2) and 48.1 plants m^{-2} (D3). Therefore, we recommended an earlier sunn hemp planting at a medium density to improve biomass, maize grain yield and economic benefits in the semiarid areas.

Data availability statement

The datasets presented in this article are not readily available because the experiments are still ongoing. Requests to access the datasets should be directed to dzvenea@gmail.com.

Author contributions

AD, WT, SW, and GC conceptualized the research idea, designed the research, monitored data collection, analyzed the data, draft, and write the final 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.

Publisher's note

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Appendix

Appendix A1 Effects of planting density on biomass and seed yield of sunn hemp at maturity harvest under the in-field rainwater harvesting technique in the central semiarid area of the Free State Province, South Africa.

	Biomass yield (Kg ha^{-1})				Seed yield (Kg ha^{-1})			
Planting period (P)	D1	D2	D3	Mean	D1	D2	D3	Mean
SSH	4225.17^{c}	10234.67^{a}	9041.50^{ab}	7833.78^{a}	459.42^{b}	1029.67^{a}	917.83^{a}	802.31^{a}
P1	3728.83^{c}	9355.50^{ab}	8632.50^{b}	7238.94^{a}	463.50^{b}	911.33^{a}	962.50^{a}	779.11^{a}
Mean	3977.00^{c}	9795.08^{a}	8837.00^{b}		461.46^{b}	970.50^{a}	940.17^{a}	
p-value		0.841				0.459		
$LSD_{(0.05)}$		–				–		
CV (%)		13.75				20.76		

SSH, sole sunn hemp; P1, simultaneous sunn hemp and maize planting; D1-low, 16.1 plants m^{-2}; D2-medium, 32.1 plants m^{-2}; D3-high, 48.1 plants m^{-2}. Means followed by the same letter in a column for each treatment are not significantly different according to LSD (0.05). *, ** Significant at $p < 0.05$, 0.001 probability level, CV is Covariance of sample.

Appendix A2 Effects of planting density on net benefits (NB), replacement value of sun hemp (RVsh), relative net return index (RNRI), maize income equivalent ratio (IERm), sunn hemp income equivalent ratio (IERsh), and income equivalent ratio (IER) at sunn hemp maturity harvest under the in-field rainwater harvesting technique in the central semiarid area of the Free State Province, South Africa.

Plant density (D)	Net benefits	RVT	RNRI	IER_m	IER_{sh}	IER
D1	797.59^{b}	1.70^{b}	1.77^{b}	1.06^{ab}	1.01^{a}	2.07^{a}
D2	1263.22^{a}	2.30^{a}	2.43^{a}	1.11^{a}	0.90^{a}	2.00^{a}
D3	1167.48^{a}	2.15^{a}	2.28^{a}	0.89^{b}	1.08^{a}	1.97^{a}
p-value	0.003**	0.002**	0.002**	0.066	0.318	0.646
$LSD_{(0.05)}$	268.10	0.33	0.33	–	–	–
CV (%)	19.97	12.76	12.19	12.12	20.12	9.10

D1-low, 16.1 plants m^{-2}; D2-medium, 32.1 plants m^{-2}; D3-high, 48.1 plants m^{-2}. Means followed by the same letter in a column for each treatment are not significantly different according to LSD (0.05). *, ** Significant at $p < 0.05$, 0.001 probability level, CV is Covariance of sample.

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No-till improves selected soil properties, phosphorous availability and utilization efficiency, and soybean yield on some smallholder farms in South Africa

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Some of the limiting factors for smallholder farmer soybean production in South Africa are low native soil phosphorus (P) availability and poor utilization efficiency of added P. Phosphorus fertilization, use of improved or high yield potential cultivars and appropriate cropping systems could increase soybean yields. The objective of this study was to determine the effects of tillage, cultivar and P fertilization levels on P uptake and P use efficiency, as well as plant growth, yield, grain protein and oil content, in a soybean based cropping system. The study was conducted under dryland conditions at Sheepmoor, Mpumalanga. A field experiment was established in a randomized complete block design. Treatments were arranged in a 2 × 3 × 3 strip-split-plot structure. There were two tillage systems [no-till (NT) and conventional tillage (CT)], three cultivars (PAN 1614R, PAN 1521R, and PAN 1532R), and three phosphorus rates (0, 30, and 60 kg/ha). All treatment combinations were replicated three times. P uptake improved with P application, although there were no differences between 30 and 60 kg/ha whilst PFP was significantly higher at 30 kg/ha P. Yield was significantly higher at 30 kg/ha P application under NT and varied with cultivars. P application at 30 and 60 kg/ha significantly reduced oil content by 11.3 and 7.16%, respectively, but had inverse effects on protein content. The activities of acid phosphatase (ACP) and alkaline phosphatase (ALP) also increased with P application. Improvement of soybean yield and its attributes, grain quality, P uptake, PFP, soil physicochemical and microbial properties emphasize the importance of fertilizer application, sustainable cropping systems coupled with careful cultivar selection. Therefore, in order to improve soil fertility and soybean yield under small farm conditions, the application of no-till and optimum application of fertilizers should be prioritized.

KEYWORDS

phosphorus, no-till, P use efficiency, soybean, smallholder farmers, alkaline phosphatase, acid phosphatase, yield

Introduction

A major limiting factor for soybean production in South Africa is low soil phosphorus (P) availability together with inefficient utilization of added P (Mabapa et al., 2010; Roberts and Johnston, 2015). Compounding this are the risks of crop failure posed by climate change (Mall et al., 2017; Mohanty et al., 2017). Despite these challenges, soybean is the world's most traded oil seed and has the potential of being Africa's Cinderella crop (Kolawole, 2012; Lee et al., 2016). The demand for soybean is very high and increasing with the increasing population (Dlamini et al., 2013; Phiri et al., 2016; Ronner et al., 2016), however, yield is still fixed at an average of 1.1 t/ha for decades (Khojely et al., 2018). In South Africa, soybean is one of the country's main commodities and its production, promotion and processing has gained some priority in the country's industrial plans since 2010 (Dlamini et al., 2013). The area under soybean production has relatively increased to about 800,000 ha since 1903 when the crop was initially introduced to South Africa (Khojely et al., 2018; DALRRD, 2020), however, average yields are still lower than experimental yields due to drier climate and low fertility soils (Phiri et al., 2016; Ronner et al., 2016; Sithole et al., 2016). For optimal yields, soybean requires between 15 and 18 mg/kg P in the soil (FERTASA, 2016). However, most soils in smallholder farming areas in South Africa are low in available P, averaging <10 mg/kg Bray 1 (Nziguheba et al., 2016).

Phosphorus is the most crucial nutrient for soybean due to its fundamental role in root establishment, grain formation and enhancement of vegetative growth (Chien et al., 2011; Shen et al., 2011). It also regulates various enzymatic activities, required for energy intensive processes in root nodule and N-fixation (van de Wiel et al., 2016; Liu et al., 2018; Mitran et al., 2018). Phosphorus also promotes higher yield and better grain quality (Mokoena, 2013). Significant positive correlations between the crop's P uptake and seed yield on soybean has been reported (Abbasi et al., 2010). According to Zheng et al. (2010), phosphorus availability could also improve root morphology even when water deficiencies occurred at reproductive stage. Phosphorus also improves plant biomass and increases P utilization efficiency (Abbasi et al., 2010). Therefore, enhancing P utilization efficiency is vital in improving crop yields and reducing eutrophication risks (Hasan et al., 2016; Heuer et al., 2017). However, the utilization efficiency is affected by factors such as, P availability, P fertilization rate and seed genotype (Syers et al., 2008; Mitran et al., 2018). A research report by Dalshad et al. (2013) from an experiment conducted at the University of Salahaddin/Erbil in Iraq, showed increased P plant uptake by 99–280.49% on various soybean cultivars after application of superphosphate at 75 kg/ha. Furthermore, one of the cultivars used, cultivar 44NK, recorded an increase of up to 10.08 and 55.56% on phosphorus fertilizer use efficiency (FEP) as well as physiological phosphorus use efficiency (PUE*p*), respectively. Abbasi et al. (2010) after observing an increased P uptake with soybean, also noted that as P rates increased P-use efficiency decreased, and therefore concluded that the low recovery efficiency could be a result of high P fixation rate by Ca compounds or Fe/Al oxides.

Fixation of P is a common challenge in many agricultural soils (Shanker and Shailendra, 2014). Although phosphorus may be abundant in many soils with a range of 100–2,000 mg/kg soil, representing nearly 350–7,000 kg/ha P in the top 25 cm layer of soil (depending on parent material, soil texture, vegetation cover and soil management history), ∼50% of the world's productive lands are deficient in P (Grant et al., 2005; Owen et al., 2015; Heuer et al., 2017). Furthermore, about 30% of global soils have a high P-fixation capacity (van de Wiel et al., 2016; Menezes-Blackburn et al., 2018). Consequently, even when phosphorus is available in large quantities in the soil, ∼80% is unavailable to the plant immediately after application (Roberts and Johnston, 2015; Zhu et al., 2018), because <0.1 % is in orthophosphate form, which plants can easily uptake (Raliya et al., 2016; Garland et al., 2018). Recent studies, however, do not support the general perception of fixation of all soil residual phosphorus (Roberts and Johnston, 2015; Zhu et al., 2018; Yan et al., 2020). Syers et al. (2008) proposed that inorganic phosphorus in the soil moves through four different P pools that vary in availability. The four main pools are (1) P in soil solution, (2) surface absorbed P, (3) strongly bonded or absorbed P, and (4) very strongly bonded or precipitated P. The first two pools contain readily available and extractable P with the first pool having immediately available P for plant use. The last two pools contain P that is not readily available. The availability of P depends on the amount accessible to plant roots. Standard laboratory methods such as Bray, Mehlich and Olsen are often used to measure soluble P, which act as indices of available P, however, the extractants do not measure the P transformed in fixed forms.

There are of a number of P activators for improving soil available P. These include phosphate solubilizing microorganisms (PSM's), phosphatase enzymes and enzyme activators (Satyaprakash et al., 2017; Zhu et al., 2018). Acid and alkaline phosphatases are the most abundant enzymes involved in solubilizing organic P compounds. These can be easily detected due to their sensitivity to disturbance (Balota et al., 2004). Phosphatases play a role in mobilizing soil P and reallocating a plant's internal P (van de Wiel et al., 2016). Nonetheless, soil biological as well as physicochemical factors such as OM, pH, nutrients, and microorganisms affect their activities (Piotrowska-Dlugosz and Wilczewski, 2014). Phosphatases highly correlate with organic matter and some studies reported significantly high activities of Acid Phosphatase (ACP) and Alkaline phosphatase (ALP) following manure or compost application (Mohammadi, 2011; Zhu et al., 2018).

Heidari et al. (2016) noted an improvement in ACP, ALP, and Dehydrogenase activities by up to 90, 60, and 148% on a treatment that had a combination of farmyard manure and compost as compared to control, which had zero fertilizer. This further supports that organic inputs improve soil microbial activities and increase microbial biomass (Heidari et al., 2016). Moreover, soil organic matter acts as an organic medium for soil enzymes (Lemanowicz et al., 2016). Mineral fertilizers also have effects on phosphatase activity; nonetheless, contrasting results have been reported. Some authors have reported an increase in phosphatase activities following fertilization, and some reported the opposite. Chen et al. (2018) reported the highest activities of phosphatase from a treatment that had a combination of P, K, and N fertilizer at 39, 112, and 276 kg/ha respectively, from a study with six fertilizer treatments conducted in China. The six treatments were as follows: CK—soil without fertilizer; N1—low N fertilizer; N2—high N fertilizer; N2P—N2 fertilizer and P; N2K—N2 fertilizer and K; N2PK—N2 fertilizer, P and K. 138 kg N/ha and 276 kg N/ha was applied in N1 and N2 treatments, respectively. 39 kg P/ha and 112 kg K/ha was applied in the N2PK treatment. However, Zhang et al. (2015), noted a significant decrease of ACP activities at a range between 11 and 63% following application of 59 and 88 kg/ha of NPK mineral fertilizer, respectively.

An intervention being advocated for enhancing soil and water productivity in cultivated areas is no till. This is due to its cost effectiveness, environmental sustainability and efficient in P conservation and cycling (Moraru and Rusu, 2013; Ramesh et al., 2014). Promoting practices such as no-till, which improve soil aggregate stability and hence soil organic carbon concentrations within the aggregates could also increase availability of phosphorus in smallholder arable lands (Busari et al., 2015). No-till increases micro-organisms' diversity (Vukicevich et al., 2016) and also increases and stratifies soil enzymatic activities (Bowles et al., 2014; Rincon-Florez et al., 2016), probably resulting from increases in organic matter and microbial activity (Sithole et al., 2016).

There is enormous literature on soil P dynamics and crop responses to phosphorus fertilization, however in South Africa (SA), the effects of P fertilization on soybean under no-till is still lacking. Moreover, most of the studies were carried out on experimental farms rather than smallholder farmer's fields. Blanket recommendations for fertilizer applications have been made, however they may not meet the requirements of a small farm specific needs (Mabapa et al., 2010). Furthermore there is limited research on no-till practices and P dynamics especially within smallholder production farms with acidic soils in SA. According to Sithole et al. (2016), the adoption rate for conservation agriculture practices such as no-till stands at 2.8% on the total country's agricultural land. Therefore, this study aimed to determine the availability and utilization efficiency of soil P to maximize soybean yields under no-till.

Materials and methods

Site description

The study was conducted in Sheepmoor, Mpumalanga. The farm is situated at 26°45′′18′S, 30°13′′58′E at an altitude of 1,537 m in Gert Sibande District Municipality, ∼45 km from Ermelo town. Sheepmoor is described as temperate dry winter and warm summer. Average rainfall is about 756 mm per annum. Minimum temperatures are between 7 and 8°C and maximum temperatures are between 26 and 30°C. Soils of the study site are sandy loam with a strongly acidic pH of 4.6. The particle size analysis indicated the soils had 20% clay, 10% silt, and 70% sand in 0–30 cm depth. Soil available P was 11.14 mg/kg, which according to FERTASA (2016) is low for soybean production and justifies the need for P amendments. The soil also had lower concentrations of soil exchangeable Ca, Mg, and K, which were 160.07, 66, and 159.4 mg/kg, respectively. Organic C and total N were 1.19 and 0.072%.

Experimental design

A randomized complete block design (RCBD) arranged in a 2 × 3 × 3 strip-split-plot layout was used to study the availability of soil P and utilization efficiency of added P in a soybean cropping system. The treatments were composed of two tillage systems, No-till (NT) and Conventional tillage (CT) as main plots (vertical rows), three soybean cultivars (PAN 1532R; PAN 1521R; and PAN 1614R) as sub plots (horizontal rows) and three Phosphorus fertilizer rates (0, 30, and 60 kg/ha) as sub-sub plots (intersection plots) replicated three times to give 54 plots. Phosphorus fertilizer source used was Monoammonium phosphate (MAP). Fertilizer was applied by banding at 5–7 cm away from the seed furrow. Each plot consisted of six 7 m long soybean rows with an inter and intra-row spacing of 60 and 5 cm, respectively (gross plots), targeting a population of 300,000 plants per hectare. The net plots consisted of four middle rows of the gross plots. The three soybean cultivars were selected based on performance in a preliminary study conducted by the ARC-SCW at the study site. The use of three soybean was done in order to determine possible differences in growth, productivity and P-use efficiency as influenced by contrasting soybean varieties.

Trial management

After trial demarcation, conventional tillage was done using a tractor-drawn mouldboard plow. Plots demarcated for no-till were treated with N-[phosphono-methyl] glycine, 360 g L-1 (Roundup) at a rate of 4 L per hectare to eradicate weeds; before planting and throughout the season. Weeds were eradicated through direct application using a knapsack sprayer to avoid contact with main crop. Furrows for direct seeding were created using hand hoes and seeds were placed manually in the furrows using a marked row after direct fertilization had been done at ratios explained on Section Experimental design. Scouting for pests and diseases was done every second week during the growing season, however, no agro chemicals were administered as there were no diseases and harmful pests observed.

Sampling and data collection

Prior to establishment of experiments, three composite soil samples from five sub samples per block were collected randomly at a depth of 0–30 cm in October 2016. Samples were air dried and passed through a 2 mm sieve and then used for initial soil characterization (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990). To evaluate the effects of treatments on soils, three sub-samples samples were randomly taken per plot with an auger at the 30 cm depth after harvest in July 2018. The following parameters were analyzed: soil solution pH was measured in water at a 1:2.5 soil water ratio as described by Okalebo et al. (2002) using a pH meter. The same suspension was used to measure electrical conductivity (EC) after allowing them to settle for 1 h using an EC meter (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990). Total N was determined using the dry combustion method using the Flash 2000 CHNS-O Analyzer. Phosphorus was extracted by P-bray 1 solution and analyzed with a flow analyzer, (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990). K+, Ca2+, Na+, and Mg2+ were extracted with ammonium acetate solution and analyzed with an Induced Coupled Plasma (ICP-OES). Fe was extracted with HCl and analyzed with ICP. Al was determined through titrable acidity method using sodium hydroxide (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990).

Bulk density was determined using the core method as described by Bonin and Lal (2012). Three random samples were collected from each plot using a core sampler. The samples were weighed immediately after collection and later transported to the laboratory for drying. Samples were oven dried for 24 h at 105°C and then weighed again. Bulk density was then calculated as the ratio of mass of dry soil per unit volume of soil cores. Penetration resistance was randomly measured from five points in a plot using a push-cone penetrometer with a measuring range of 0–40 mm. The penetrometer measured a resistance of soil by pushing a cone vertically into the profile. Activities of acid and alkaline phosphatase were evaluated as described by Tabatabai (1994). These enzyme activities were analyzed using 1 g of air-dried soil in a 50-ml Erlenmeyer flask with their appropriate substrate and incubated for 1 h (37°C) at their optimal pH (pH 6.5 for assay of acid phosphatase or pH 11 for assay of alkaline phosphatase). Enzyme activities were evaluated in duplicate with one control, to which, substrate was added after incubation and subtracted from the sample value.

A measuring stick was used to measure plant height during crop maturity by measuring crop length from base to the top leaf. Days to 50% flowering were recorded as the day on which half the crops in each plot flowered. The number of pods per plant (NPP), pod length and number of seeds per pod were counted manually from three plants randomly selected from the net plots at crop maturity. The maturity date was recorded when the crops had turned golden yellow. Soybean net plots were harvested manually into grain bags; grain weight was measured with a digital scale after shelling. Three plants from boundary rows were used to measure wet shoot biomass with a digital scale and then taken to the laboratory for dry biomass measurements after oven drying the samples for 24 h at 70°C. A moisture meter (Dramiński Twistgrain) was used to measure grain moisture at harvest according to the instrument's instruction manual. 100-seed weight was measured by counting 100 seeds and then weighing them on a digital scale. Grain protein and oil content were measured by DA 7250 NIR analyzer (Perten Instruments, Hägersten, Sweden) following a non-disruptive method as stipulated in the instruction manual of the instrument. The sample was poured into an open-faced dish and placed in the machine. Results were viewed on the screen of the machine. Yield was calculated using the following equation and expressed in tons per hectare:

$$Y\left(t/ha\right) = \frac{100 - moisture\ \%}{100 - 12} \times seedmass$$

Where 12% is the adjusted moisture (Verde et al., 2013).

Plant N was analyzed using the dry oxidation method on a Flash 2000 CHNS-O Analyzer whilst P and K were analyzed following digestion with Nitric + Perchloric acid on an Agilent 725 (700 Series) Inductively Coupled Plasma Optical Emission Spectrometric (ICP-OES).

P use efficiency was calculated using the balance method as follows:

$$P\ use\ efficiency\ (\%) = \frac{P\ taken\ up\ by\ the\ crop\ under\ fertilized\ soil}{amount\ of\ P\ applied} \times 100$$

Partial factor productivity (PFP), which measures the utilization efficiency considering production productivity was determined by dividing yield by amount of P applied. It indicates the productivity of a crop (yield) in comparison to the fertilizer applied Roberts and Johnston (2015).

Statistical analysis

Analysis of variance (ANOVA) and correlations were performed using JMP 14 (Ramirez and Ramírez, 2018). Mean separations were done using Fishers' protected least significant differences (LSD) at $P < 0.05$. Correlations were performed using Pearson's correlation test.

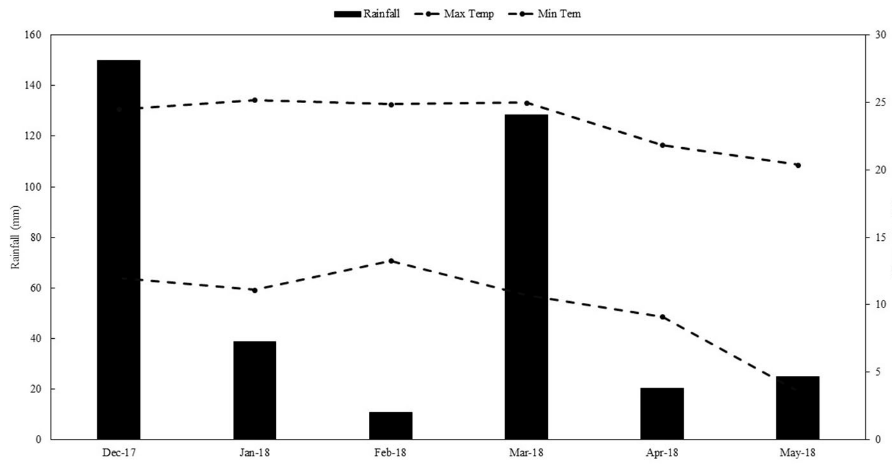

FIGURE 1
Climate data of the study site during the planting season.

Results and discussion

Climatic data during the planting season and results from the initial soil characterization are presented in Figure 1 and Table 1, respectively.

TABLE 1 Initial soil characterization.

Soil property	Units
pH	4.6
EC (mS/cm)	22
Total *N* %	0.072
Organic C %	1.19
P (mg/kg)	11,14
K (mg/kg)	159.4
Ca (mg/kg)	160.07
Mg (mg/kg)	66.7
Na (mg/kg)	0.56
Bulk density g cm^{-3}	1.2
Sand %	70
Silt %	10
Clay %	20

Fertilizer and tillage effects on soil properties

Significant effects ($P < 0.05$) of fertilizer application were observed on exchangeable calcium (Ca) and magnesium (Mg), Iron (Fe), total Nitrogen (TN), exchangeable phosphorus (P), and exchangeable potassium (K) concentrations (Table 2). Application of 30 kg/ha P significantly increased levels of extractable Ca, Mg, K, and TN by up to 61.87, 52.91, 33.12, and 11.59%, respectively, over the control. However, at the 60 kg/ha P rate exchangeable Ca, Mg, K, and TN were statistically lower than those observed after the application of 30 kg/ha P, whereas available P gradually increased up to 97.23% over control, and recorded the highest soil P levels at 60 kg P/ha application rate. On the contrary, application of 30 kg/ha P caused a significant decrease in extractable Fe, whereas at 60 kg/ha, the amount of Fe equivalent to control.

Soil pH was not significantly affected by fertilizer application whilst extractable Aluminum (Al) was not significantly affected by any of the main treatments. Meanwhile, pH, exchangeable Ca, Mg, and K were significantly affected ($P < 0.05$) by tillage (Figure 5). No-till led to the increase of pH, exchangeable Ca, Mg, and K by up to 1.76, 20.64, 23.77, and 15.08% over CT, respectively. Tillage had no significant effects on Fe, Al, and P (Table 2). Out of the selected physical properties, bulk density (BD) was not affected by any of the main treatments, whereas penetration resistance was significantly affected ($P < 0.05$) by tillage.

Exchangeable cations such as Ca and Mg are usually low in strongly acidic soils (Fageria and Baligar, 2005). However, the increase of Ca and Mg at 30 kg/ha P could be a result of lower Fe concentration at the same fertilizer rate and vice versa at 60 kg P/ha application. Iron and Aluminum, like many metals, are predominantly found in strongly acidic soils such as the experimental site (Lemanowicz et al., 2016; Heuer et al., 2017). Therefore, significant decrease of Fe at 30 kg/ha P could be due to fixation: Fe/Al oxides fix more than 80% of applied P; this reaction may significantly reduce Fe and available P in the soil solution (Heuer et al., 2017; Zhu et al., 2018). Literature has also shown that Fe uptake by plants is sensitive to excessive P

TABLE 2 Effects of fertilizer, cultivar and tillage on soil physico-chemical properties on a soybean cropping system.

Treatment			mg/kg						g/cm³	kPa
	pH	TN %	Ca	Mg	Fe	Al	P	K	Bulk density	Penetration resistance
Fertilizer (F)										
0	4.58a	0.067c	101.44b	43.39b	31.59a	1.66a	11.054c	95.33c		
30	4.62a	0.075a	164.2a	66.34a	24.62b	1.86a	21.802b	126.90a		
60	4.53a	0.071b	111.4b	50.28b	30.35a	1.79a	37.159a	109.54b		
P-value	ns	0.0289	<0.0001	<0.0001	0.0031	ns	0.0004	<0.0001		
Cultivar (C)										
PAN 1614R	4.55a	0.052a	118,11a	50.56a	27.27a	1.84a	27.84a	107.55a		
PAN 1521R	4.61a	0.055a	125,89a	55.11a	29.02a	1.65a	32.24a	113.00a		
PAN 1532R	4.56a	0.055a	118,11a	54.34a	30.27a	1.84a	35.37a	111.21a		
P-value	ns	ns	ns	ns	ns	ns	ns	ns		
Tillage (T)										
NT	4.62a	0.054a	137,44a	59.00a	27.8a	1.72a	30.01a	118.35a	1.47a	693.64b
CT	4.53b	0.053a	113.92b	47.67b	29.91a	1.83a	33.62a	102.83b	1.50a	1,249.79a
P-value	0.0184	ns	0.0081	0.001	ns	ns	ns	0.0004	ns	0.0017
Interactions										
C × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C × F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T × F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C × T × F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Levels with different letters not connected by same letter are significantly different ($P < 0.05$; Fisher's test).
NT, no-till; CT, conventional tillage; ns, not significant.

(Murphy et al., 1981); therefore, surplus P may cause inhibition of Fe from plant root uptake, and thus making Fe available at higher concentrations in the soil solution (Murphy et al., 1981; Fageria, 2001).

The increase of TN and a progressive increase of P from 30 to 60 kg/ha in soil solution could be a result of supply of phosphates and ammonia from fertilization (Aniekwe and Mbah, 2014; Zhang et al., 2015; Yin et al., 2016) (Table 2). A significant decrease in TN at 60 kg/ha P as compared to 30 kg/ha P (Table 2) may be a result of plant N uptake, which was significantly higher at 60 kg/ha P (Table 4). This is because adequate supply of P in the roots of soybean increases root biomass and nodulation, which facilitates nitrogen fixation (Mitran et al., 2018).

The increase of exchangeable Ca^{2+}, Mg^{2+}, and K^{+} under no-till could be due to residue retention (higher organic matter accumulation), which through decomposition, releases nutrients back into the soil (Malecka et al., 2012; Sithole et al., 2016). The increase of both Ca and Mg could be responsible for the increase in pH under NT. Similarly, Busari et al. (2015) noted that increasing tillage disturbance decreases soil surface pH, and that CT shifts top fertile soils into the sub-soil, and the less fertile sub-soils onto the surface. Moreover, due to a loose soil structure under CT, loss of nutrients through erosion is also a possibility.

Lower PR and BD were observed under NT as compared to CT, but only PR was affected significantly ($P < 0.05$; Table 2). This is because PR is more sensitive to changes than BD (Moraru and Rusu, 2013). However, literature has contrasting reports on PR and BD under no-till. Some studies reported a stable or higher PR and BD on no-till especially at the 0–10 cm layer (Jabro et al., 2011; Malecka et al., 2012; Villamil et al., 2015; Sithole et al., 2016), whilst others observed the opposite (Malecka et al., 2012; Sharma et al., 2016). However, data from some long-term studies indicate a shift on bulk density as years progress. Sharma et al. (2016) observed higher soil BD under NT within the initial 5 years of the experiment, however after 10 years a reverse trend was observed. This makes the duration of the experiment an important factor especially for soil physical characteristics. The lower penetration resistance in the current study could be a result of soil moisture retained under crop residues through higher production of biomass, which ultimately improved soil structure under NT (Bogunovic et al., 2019). The benefit of lower penetration resistance in no-till systems is root elongation, proliferation and plant nutrient uptake (Moraru and Rusu, 2013).

Soil enzyme activities were significantly affected ($P < 0.05$) by fertilizer and tillage at various growth stages (Table 3). The activities of ACP increased by up to 36% at reproductive stage under no-till as compared to CT. This is because no-till is

TABLE 3 Fertilizer application, cultivar and tillage effects on acid phosphatase and alkaline phosphatase activities on a soybean cropping system.

	p-nitrophenol mg/kg/h					
	Vegetative stage		Reproductive stage		Maturity stage	
Treatment	**ACP**	**ALP**	**ACP**	**ALP**	**ACP**	**ALP**
Fertilizer (F)						
0	2,164.5b	219.88a	1,656.45b	64.58b	2,297.03b	169.49b
30	3,223a	369.08a	2,643.75a	226.76a	5,788.20a	299.68a
60	2,009.1b	242.52a	1,518.98b	84.97b	2,873.77b	159.47b
P-value	0.0081	ns	0.0019	0.0265	<0.0001	0.0485
Cultivar (C)						
PAN 1614R	2,455.77a	245.74a	1,930.70a	104.88a	104.88a	220.09a
PAN 1521R	2,353.38a	292.65a	2,086.25a	114.88a	114.88a	182.05a
PAN 1532R	2,587.47a	293.09a	1,802.24a	156.55a	156.55a	226.50a
P-value	ns	ns	ns	ns	ns	ns
Tillage (T)						
NT	2,743.67a	240.11a	2,235.62a	131.19a	4,130.94a	234.46a
CT	2,187.42a	314.21a	1,643.83b	119.69a	3,175.06a	184.63a
P-value	ns	ns	0.0262	ns	ns	ns
Interactions (*P*-value)						
C × T	ns	ns	ns	ns	ns	ns
C × F	ns	ns	ns	ns	ns	ns
T × F	ns	ns	ns	ns	ns	ns
C × T × F	ns	ns	ns	ns	ns	ns

Levels with same letter are not significantly different ($P < 0.05$; Fisher's test).
ns, not significant; NT, no-till; CT, conventional tillage; ACP, Acid phosphatase; ALP, Alkaline phosphatase.

effective in improving soil enzyme activities in the short-term (Heidari et al., 2016). According to Sithole et al. (2016), the increase in soil enzymes activities under no-till could be a results of the increase in stratification of enzymes close to the soil surface due to increased soil organic matter. Balota et al. (2004) also reported an increase of ACP and ALP up to 46 and 61% at top soil layer under no-till, respectively.

Phosphorus application at 30 kg/ha caused a significant increase of ACP activities by up to 48.93, 59.59, and 151.99% at vegetative, reproductive and maturity stage, respectively, over control. Whereas for AL P, significant increases were only noted during reproductive and maturity stages by up to 251.13 and 76.81%, respectively, over control. The activities of ACP were generally higher than ALP due to the strongly acidic pH. According to Sharma et al. (2013), acid phosphatase are usually the dominant group of enzymes involved in mineralizing P in acidic soils whilst alkaline phosphatase enzymes are dominant in alkaline soils. The difference in enzyme activities were not significant at 60 kg/ha P. Phosphatase activities could have been suppressed by an increase of inorganic phosphorus in the soil because more often, phosphatases activities are inversely proportional to available soil P concentration (Wang et al., 2013; Lemanowicz et al., 2016). Heidari et al. (2016) also reported a suppression of phosphatase activities due to fertilization. This may suggest that P rate up to 30 kg/ha could be the optimum level for high phosphatase activities in the study area.

Plant NPK uptake and P utilization efficiency

Application of P improved uptake of N, P, and K significantly ($P < 0.05$), however, excessive application of P above 30 kg/ha did not enhance uptake significantly except for N (Table 4). For P and K, the highest uptake was observed at 60 kg/ha P rate, although it was statistically similar to 30 kg/ha P rate. Whereas for N, there was a significant progressive increase at 30 and 60 kg/ha P. Nutrient increases were as follows: at 30 kg/ha P rate, uptake of N, P, and K increased by up to 21.74, 91.51, and 69.05%, whilst at 60 kg/ha P rate the increase was up to 34.78, 119.82, and 75.76%, respectively, over control. Aulakh et al. (2003) and Sharma et al. (2011) also reported increase in nutrient uptake following P application, however, excessive P did not have agronomic benefits such as increase in yield, biomass or biomass partitioning to grain. Findings of the current study confirmed reports from several researchers who argued that

TABLE 4 Effects of fertilizer, cultivar and tillage on plant nutrient uptake on a soybean cropping system.

Treatment	%	kg/ha	
Fertilizer (F)	***N***	**P**	**K**
0	0.23c	11.20b	70.62b
30	0.28b	21.45a	119.38a
60	0.31a	24.62a	124.12a
P-value	0.026	0.017	0.043
Cultivar (C)			
PAN 1614R	46a	17a	54a
PAN 1521R	49a	14a	38ab
PAN 1532R	46a	15a	33b
P-value	ns	ns	0.0483
Tillage (T)			
NT	54a	15a	39a
CT	61a	15a	44a
P-value	ns	ns	ns
Interactions (*P*-value)			
C × T	ns	ns	ns
C × F	ns	ns	ns
T × F	ns	ns	ns
C × T × F	ns	ns	ns

Levels with same letter are not significantly different ($P < 0.05$; Fisher's test).
NT, no-till; CT, conventional tillage; ns, not significant.

TABLE 5 Pearson's correlation test on plant nutrient uptake (N, P, K) with dry biomass on a soybean cropping system.

	Kg/ha			g
	P	**K**	***N***	**Dry biomass**
Dry biomass	0.71*	0.73*	0.70*	1

*P < 0.0001.

nutrient uptake is correlated with biomass production (Sharma et al., 2011; Dalshad et al., 2013; Fageria et al., 2013) (Table 5).

Main treatments and their interactions had no significant effects ($P < 0.05$) on P use efficiency (Table 6). The utilization efficiency at 30 and 60 kg P/ha rate was 19.65 and 15.82%, respectively. This is considered to be a very low utilization efficiency. Usually, a P use efficiency calculated using the balance method should be in the range of 50–70% but can even be higher than 100% if the crop also utilized some of the P reserves in the soil. A very low P utilization efficiency recorded for this study could suggests a high fixation capacity of soils and/or more fertilizer was applied than what was needed for the crop (Roberts and Johnston, 2015). Nonetheless, partial factor productivity (PFP) which only focuses on seed yield indicating crop productivity in relation to its nutrient input was significantly affected ($P < 0.05$) by P rate. PFP increased by up to 105.79% at 30 kg/ha over 60 kg/ha P. Syers et al. (2008) and Abbasi et al. (2010) reported that as P rate increase P-use efficiency decreased. This therefore means P supply at 60 kg/ha rate exceeded the requirement for optimum crop production (Roberts and Johnston, 2015).

TABLE 6 Fertilizer effects on P use efficiency and Partial factor productivity on a soybean cropping system.

Fertilizer	P use efficiency %	Partial factor productivity Kg/kg P
0 kg/ha	-	-
30 kg/ha	19.76a	68.46a
60 kg/ha	15.82a	33.26b
P-value	ns	<0.0001

Levels with same letter are not significantly different ($P < 0.05$; Fisher's test).
ns, not significant.

Fertilizer application, tillage and cultivar effects on soybean growth, yield components, and grain quality

Fertilizer, cultivar and tillage had significant effects on crop growth and yield components (Table 7). Number of pods per plant (NPP) and plant height increased progressively with P application by up to 66.15 and 21.31%, respectively, over control. However, these increases were statistically similar at 30 and 60 kg/ha P. Tillage and cultivar did not have any significant effects ($P < 0.05$) on NPP, however, cultivar had significant effects on plant height. Tillage did not significantly affect plant height, and in addition, fertilizer and tillage did not significantly affect 100-seed mass and pod length. The 100-seed mass, pod length together with plant height were significantly affected ($P < 0.05$) by cultivar (Table 7). PAN 1614R recorded the highest 100-seed mass (16.85 g), longest pods (4.11 cm) and tallest plants (49.84 cm). However, for 100-seed weight the cultivars PAN 1614R and PAN 1521R were statistically similar.

A significant interaction between tillage and cultivar was observed for pod length. Under CT, PAN 1614R produced the longest pods, whilst PAN 1521R and PAN 1532R were shorter and performed similarly under both tillage systems. Under NT, PAN 1614R also performed statistically the same as PAN 1521R and PAN 1532R (Figure 2).

The increase in NPP and plant height after P application was because phosphorus in soybean is responsible for growth and pod formation (Fageria et al., 2013; Ahiabor et al., 2014). The recommended P level in the soil for soybean is between 15 and 18 mg/kg (FERTASA, 2016), and in this experiment, soils under control (0 kg/ha P) had critically low soil available P of about 11.05 mg/kg (Table 7) hence shorter plants and lower

TABLE 7 Effects of fertilizer, cultivar and tillage on number of pods per plant (NPP), pod length, plant height, and 100- seed mass on a soybean cropping system.

Treatment	NPP	Pod length cm	Plant height cm	100-seed mass
Fertilizer				
0	40b	3.93a	65.25 a	15.98a
30	67a	4.07a	64.17a	15.6a
60	65a	3.95a	46.39b	16.65a
P-value	0.0445	ns	<0.001	ns
Cultivar				
PAN 1614R	46a	4.11a	69.5a	16.85a
PAN 1521R	49a	3.9b	59.33b	15.95ab
PAN 1532R	46a	3.93b	47c	15.43b
P-value	ns	0.0199	<0.0001	0.0369
Tillage				
NT	54a	3.95a	59.33a	16.13a
CT	61a	4.01a	57.87a	16.02a
P-value	ns	ns	ns	ns
Interactions				
C × T	ns	0.0259	ns	ns
C × F	ns	ns	ns	ns
T × F	ns	ns	ns	ns
C × T × F	ns	ns	ns	ns

Levels with same letter are not significantly different ($P < 0.05$; Fisher's test).
ns, not significant; NT, no-till; CT, conventional tillage.

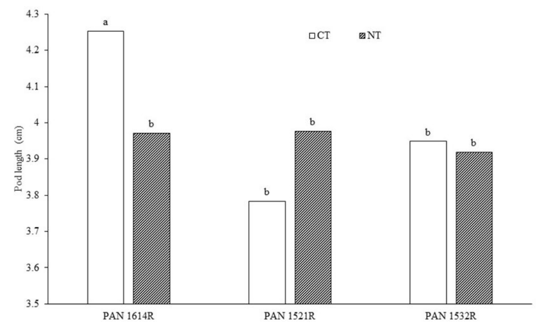

FIGURE 2
Interactive effects of cultivar and tillage on pod length on a soybean cropping system. Levels with same letter are not significantly different.

pods count. This is because low supply of P imposes major restrictions in vegetative growth and reproduction of soybean (Mitran et al., 2018). Results from Malik et al. (2006) also support these findings.

The differences in cultivar performance for 100-seed weight and plant height could be a result of genotype. This is because seed size traits are determined by several genes in a plant (Krisnawati and Adie, 2015), and mature seed sizes are simultaneously determined by embryo, cytoplasm and maternal effects (Adie and Krisnawati, 2018). Similar to 100-seed mass, plant height and the differences in pod length as a result of cultivar and tillage effects could be because of the seed genotype (Krisnawati and Adie, 2015), and adaptability to tillage system.

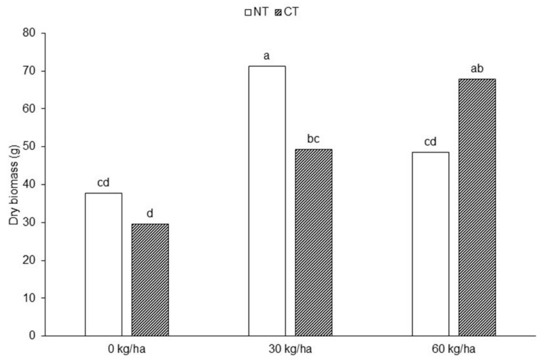

FIGURE 3
Interactive effects of fertilizer and tillage on dry biomass on a soybean cropping system. Levels with same letter are not significantly different.

Significant interactions ($P < 0.05$) between fertilizer and tillage treatments were observed on dry biomass (Figure 3). Dry biomass was significantly higher at 30 kg/ha P under NT and statistically same with 60 kg/ha P under CT. Increase of biomass after P applications have been noted by other authors (Aulakh et al., 2003; Ahiabor et al., 2014). The response of dry biomass to P additions could be attributed to increased phosphates in the soil, which make orthophosphates readily available for plant uptake and are used for various essential plant processes such as growth, development and reproduction (Shen et al., 2011). Furthermore, no-till retains soils moisture and reduces erosion, which enhances P availability and OM decomposition under NT recycles organic P back into the soil (Busari et al., 2015).

There were statistically significant interactions between P application rate, cultivar and tillage on soybean yield (Figure 4). The overall highest yield was recorded at 30 kg/ha P application under NT for PAN 1521R, however it was statistically similar to PAN 1521R under CT at 60 kg/ha and PAN 1532R under NT at 60 kg/ha P. Nonetheless, PAN 1532 performed statically same at 60 kg/ha under NT and 30 kg/ha under both NT and CT. Therefore, the optimum fertilizer rate and tillage system for all 3 cultivars was 30 kg/ha P under NT. Yield increases after P application are expected because P is the most essential element required for growth and reproduction in soybean (Chien et al., 2011; Shen et al., 2011). Phosphorus additions result in improved yields and better grain quality (Malik et al., 2006; Mabapa et al.,

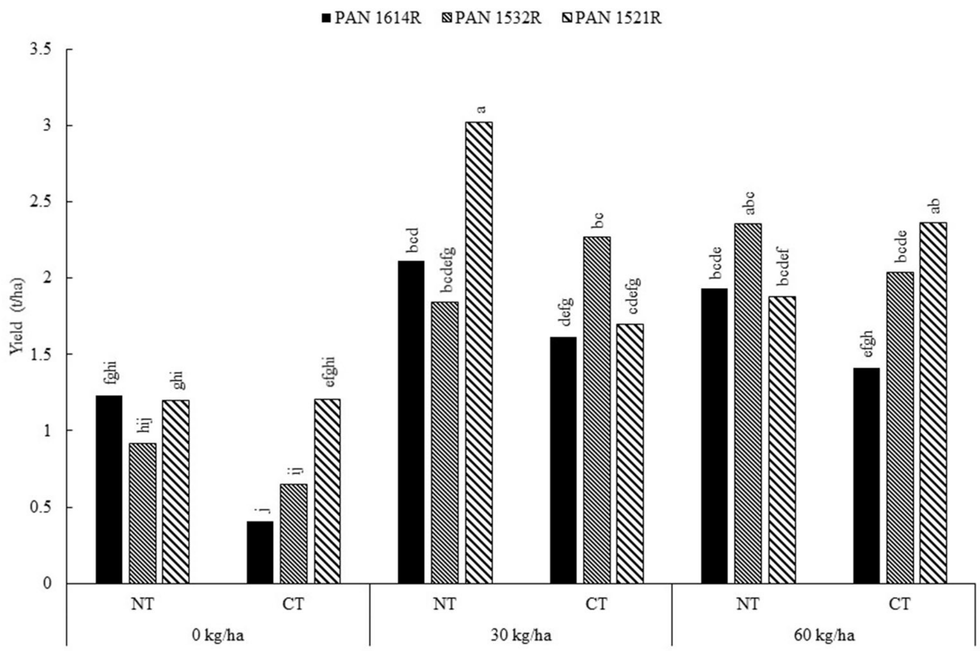

FIGURE 4
Interactive effects of fertilizer, cultivar and tillage on soybean yield on a soybean cropping system. Levels with same letter are not significantly different.

2010). This is shown by positive relationship ($P < 0.0001$, $R^2 = 0.93$) between soybean yield and plant P uptake (Figure 5).

Nonetheless, the statistically similar yield performance of PAN 1521R at 30 kg/ha P under NT, PAN 1532R at 60 kg/ha P under NT and PAN 1521R at 60 kg/ha P under CT could be because crops usually take up to 25% of the applied phosphorus in the soil (Roberts and Johnston, 2015). Therefore, adding more fertilizer may only raise the soil's P balance where no direct yield response is expected (Chien et al., 2011). Abbasi et al. (2012), reported yield increases of up to 53% with increased P application, and Malik et al. (2006) observed a statistically similar soybean yield between 90 and 120 kg/ha. Moreover, Aulakh et al. (2003) also observed increasing seed yield following P application up to 80 kg/ha, and no yield response above 80 kg/ha P rate. As for tillage, Buah et al. (2017) noted an increasing yield of soybean by up to 54% under NT as compared to CT in 2014 on a study in Ghana. Yield increases under no-till can be attributed to improved nutrient cycling through the P release by crop residues, mineralization of OM by microorganisms (Turan et al., 2017; Zhu et al., 2018), improved infiltration and storage of water, and conservation P by reducing erosion (Jabro et al., 2011; Busari et al., 2015). Yield increases under no-till especially during drier periods were reported (Busari et al., 2015).

Yield increase at 30 and 60 kg/ha P treatments resulting from increased NPP was also recorded in this study and supported by

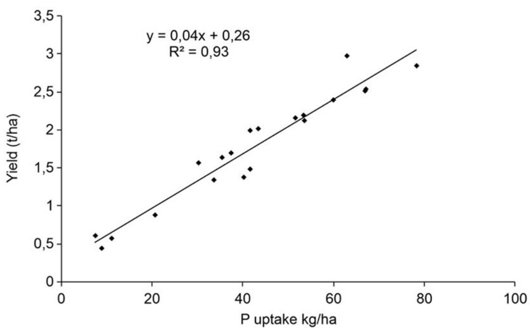

FIGURE 5
Relationship between P uptake and yield on a soybean cropping system.

significant positive correlation of yield with NPP ($P = 0.0084$; $R^2 = 0.90$) (Figure 5).

Significant effects ($P < 0.05$) of phosphorus application rate and cultivar were observed on protein and oil content (Table 8). P application at 30 and 60 kg/ha significantly reduced oil content by 7.97 and 12.17% but had inverse effects on protein content increasing it by 0.92 and 1.15%, respectively, over control. These results confirm findings by

TABLE 8 Effects of fertilizer, cultivar and tillage on oil and protein content on a soybean cropping system.

Treatment	Oil %	Protein %
Fertilizer		
0	11.42a	34.93b
30	10.51b	35.25a
60	10.03b	35.33a
P-value	0.0003**	0.0286
Cultivar		
PAN 1614R	11.31a	34.63c
PAN 1521R	10.41b	35,12b
PAN 1532R	10.23b	35.77a
P-value	0.0026**	<0.0001***
Tillage		
NT	10.41a	34.4a
CT	10.89a	34.6a
P-value	0.0634	0.7152

Levels with same letter are not significantly different.
ns, not significant; NT, no-till; CT, conventional tillage.
$^*p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$.

several authors of decreasing oil production with increasing protein content due to P application (Mokoena, 2013; Yin et al., 2016), and statistically similar protein content between P application rates (Abbasi et al., 2012). Nonetheless, the response of oil and protein content to P application have contrasting reports in literature. Some authors have reported a decrease of protein content with no significant difference in oil content following P fertilization (Win et al., 2010), whilst others have reported an increase of both oil and protein content following P application (Malik et al., 2006; Abbasi et al., 2012). However, when P is deficient in the soil, P additions improve N fixation which enhances seed protein content (Yin et al., 2016). Phosphorus is necessary for growth, development, yield and nutritive quality of soybean seed, however, excess applications may depress oil and protein content (Win et al., 2010).

Cultivar also had significant effects ($P < 0.05$) on both oil and protein content. PAN 1614R had much higher oil of up to 11.31% as compared to other cultivars, but the same cultivar had the lowest protein content of 34.63%. Contrastingly, PAN 1532R had the lowest oil content of 10.23% and the highest protein content of 35.77%. Nonetheless, correlation between oil and protein content was not significant, and this is supported by Yin et al. (2016). Other factors affecting soybean protein and oil content are genotype and the environment (Yin et al., 2016). The cultivar effect on oil and protein content could be due to 100-seed weight. It was observed that the cultivar with significantly higher 100 seed weight (PAN 1614R) contained significantly high oil and low protein content. Whereas the cultivar with significantly low 100 seed weight (PAN 1532R), the opposite is true. A positive linear relationship between oil and 100 seed weight ($P = 0.0458$; $R^2 = 0.97$), and a negative linear relationship between 100-seed weight and protein ($P = 0.002$; $R^2 = 0.94$) support these findings.

Conclusion and recommendations

This study showed that the application of mineral P fertilizer improved the soil's nutrients status by raising the soil's pH and also concentrations of exchangeable Ca, Mg, P, K, and TN whilst reducing Fe which is one of the main causes of soil acidity. The increase of pH with increasing exchangeable Ca and Mg under no-till supports the theory of nutrient cycling under no-till and suggest that this system could be a viable option of managing acidity considering that accessibility of lime to smallholder farmers in South Africa is a big challenge. However, this cannot match the benefits of lime application. Moreover, results of this study supports studies that indicate that penetration resistance responds very quickly to change, and that increase in biomass could improve penetration resistance in short-term experiments. Phosphorus application also stimulated activities of both ACP and ALK, with ACP being the dominant enzyme because of acidity. Nonetheless, excessive application of P above 30 kg/ha did not improve activities of both enzymes. The activities of both phosphatases increased under no-till at all growth stages, although only ACP at reproductive stage was significant. This suggest that no-till has the potential for higher enzyme activity, which would lead to increased soil fertility because of their role in solubilizing organic P.

Tillage, cultivar and varying mineral P levels had significant effects on P uptake and P use efficiency in a soybean experiment. The application of P significantly improved N, P, and K uptake at both 30 and 60 kg/ha P, however, no differences were observed between 30 and 60 kg/ha P rates for P and K. The lowest N, P, and K uptake was observed under control (0 kg/ha P), this indicates the need for P application and its conservation in soybean production. Phosphorus utilization efficiency was very low and did not differ statistically across P rates. This may be an indication of a higher fixation capacity of the soil due to acidity. Nonetheless, the PFP which calculates P efficiency using seed yield was significantly higher at 30 kg/ha P. This implies that farmers should apply fertilizers at standard rates, as excess P is agronomically inefficient.

Data availability statement

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

Author contributions

PC: conceptualization, methodology, formal analysis, data collection, and writing—original draft. AN: conceptualization, methodology, writing—review and editing, project administration, and supervision. IW and FM: review and editing and supervision. SM, MM and IK: review and editing and funding. 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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Profitability and agronomic potential of cotton (*Gossypium hirsutum* L.) under biochar-compost-based amendments in three agroecological zones of northern Benin

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Low land productivity is a major constraint facing agriculture in sub-Saharan Africa, which severely affects crop yields, particularly cotton which is main export agricultural produce of Northern Benin. To overcome this situation, the hill-placement of microdose biochar-compost-based amendments was carried out at two research stations and on farmer's fields in three agroecological zones of northern Benin. The study aims to evaluate the agronomic and economic performance of cotton under two types of compost and biochar-based amendments. On stations, the experimental design used was a complete randomized block with one factor and ten treatments replicated four times as follows: (i) absolute control without any amendment (Ck), (ii) mineral fertilizer (MF) at 200 kg/ha, (iii) cow dung-based compost at 200kg/ha (CP1_200) and (iv) 300kg (CP1_300), (v) household waste-based compost at 200kg/ha (CP2_200) and (vi) 300 kg (CP2_300), the combination of CP1 and 15% biochar designated Terra preta (TP) applied at 200kg/ha (vii, TP1_200) and 300kg/ha (viii, TP1_300), the combination of CP2 and 15% biochar applied at 200kg/ha (ix, TP2_200) and 300kg/ha (x, TP2_300). On-farms, the experimental design was a randomized complete block with one factor and six optimal treatments extracted from the on-station experiments with three replicates installed in four farmers' fields from each location studied. The six treatments were: Ck, MF, CP1_200, CP2_200, TP1_200 and TP2_200. Cotton growth (Plant height, number of vegetative and reproductive branches and total bolls per plant) and yield data were collected. The treatment TP1_300 yielded higher cotton seed with 2.53 t/ha, i.e., 86% more than the absolute control. However, the highest plant growth parameters were obtained with MF which were similar to those obtained with TP1_300 (P > 0.05). Likewise, at farms, the highest plant growth parameters and yield were observed with MF followed by TP1_200 (with a cotton seed yield increase of 146% compared to the control, P < 0.05). In addition, no significant differences were observed between organic fertilizers treatments for growth variables. However yield differences occurred. To resume, TP1_300 kg/ha performed best in terms of growth and yield in on-station experiments, while on-farms, TP1_200 kg/ha produced the highest responses of cotton. Value Cost Ratio (VCR) and Benefit Cost Ratio (BCR) values were generally as good or even better for MF treatment and treatments involving CP1 at both on station and on farm, compared to Ck. Although applying mineral fertilizer (MF) alone as currently done by many farmers appears to make economic sense, this practice is unlikely to be sustainable in the long term. Applying TP1_200 and TP1_300 are two possible strategies that are affordable to farmers and provide returns on investment at least as good as the current practice of sole application of MF. However, a long-term study to assess the effect of compost-activated biochar on crop productivity and soil quality is advised.

KEYWORDS

agroecology, biochar, innovation, Terra preta, northern Benin

Introduction

Cotton (*Gossypium hirsutum* L.), has been for years a lever for transformation in agricultural production systems. However, its production plays an important role in the economy of West and Central Africa (Soumaré et al., 2021). It represents nearly 30% of exports and contributes, in terms of value added to 7% Gross Domestic Product (World Bank, 2016). Despite this importance, cotton production is characterized by low productivity due to low inherent soil fertility coupled with poor agricultural practices including excessive use of mineral fertilizers (Amanet et al., 2019). The latter can contributes to long-term soil acidification (Adams et al., 2016) and a decrease in organic matter (Bationo et al., 2012; Vanlauwe et al., 2014). In addition, temperature variation and the uncertainty of rainfall patterns strongly affect the crop productivity (Rosenzweig et al., 2014; Ahmad et al., 2018; Nasim et al., 2018).

Improving soil fertility has become a mandatory step for the sustainability and productivity of production systems in West Africa savannas (Bationo et al., 2007; Koulibaly et al., 2015). However, this improvement requires the integration of sustainable land management (SLM) measures whereby bringing organic matter to the soil will lead to an increase in the carbon stock whose depletion leads to soil degradation (Lal, 2009).

Several techniques for the sustainable management of soil fertility have been tested by researchers both around the world and in sub-Sahara Africa. These practices involve the use of different forms of organic amendments viz. compost, manure, crop residues, green manure, fertilizer microdosing, etc. to improve the physical, chemical and biological properties of the soil (Akponikpe et al., 2008; Ibrahim et al., 2015; Agegnehu et al., 2016; Tovihoudji et al., 2017, 2019). Compost is an excellent fertilizer for plants because of its beneficial effects for nutrients supply to the soil including nitrogen, phosphorus, potassium and various other micronutrients (Nacro et al., 2010). It is therefore urgent to find a sustainable alternative to conventional agricultural land management by taking inspiration from traditional practices, reproducing and amplifying what nature achieves (Montaigne et al., 2018) to improve soil pH and nutrient bioavailability. In the context of global challenges (climate, input price variability, market access), meeting these expectations requires the development of sustainable and resilient land management practices from organic waste. In peasant environments, there is a wide diversity of organic substrates available for use by farmers (Blanchard et al., 2014). These include cattle, sheep, goat and poultry droppings, household wastes, and biochar from the pyrolysis of maize cobs or stalks or rice husks (green charcoal).

Biochar, "green charcoal", is the result of the slow pyrolysis of plant biomass in an oxygen-free or low-oxygen atmosphere. The result is a product with a very high carbon content (Rutigliano et al., 2014). The scientific literature on the effects of biochar is very prolific on food crops (Cornelissen et al., 2013; Nyami et al., 2016; Yeboah et al., 2016; Jeffery et al., 2017; Steiner et al., 2018; Chen et al., 2022). One of the promising technologies to improve the pH and bioavailability of soil nutrients is the combined use of biochar and organic or mineral fertilizer.

Biochar generally has a positive effect on crop yields when applied effectively to soils that are not very fertile, moderately fertile or degraded than to healthy fertile soil (El-Naggar et al., 2019). Several authors have shown that integrating biochar into highly eroded or erodable tropical soils significantly improves their physical, chemical and biological properties and crop yields (Cornelissen et al., 2013; Nyami et al., 2016; Yeboah et al., 2016; Jeffery et al., 2017; Steiner et al., 2018; Chen et al., 2022) in vegetable and cereal crops but very little information is known on the effect of biochar from maize cobs on cotton performance (Elangovan and Sekaran, 2014).

In the dynamics of ecological transition and with a view of providing the ever-growing population with quality and healthy agricultural products, the reduction of chemical inputs in favor of renewable inputs such as biochar-compost-based amendment (known as "Terra preta"; Lehmann, 2009) is a path that should

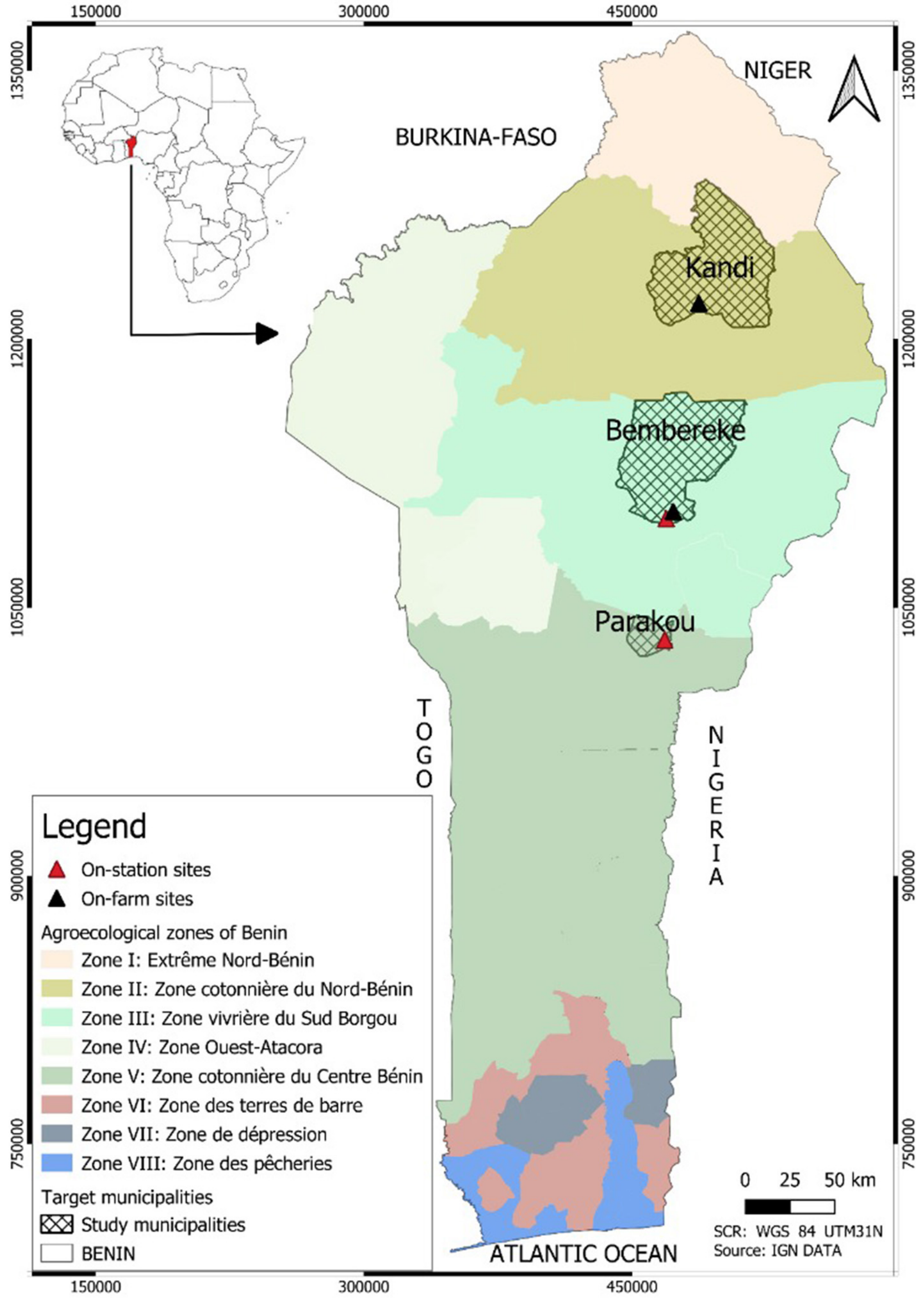

FIGURE 1
Map of Benin showing the location of the three sites (Parakou, Bembereke and Kandi) in Northern Benin.

be preferred. The present study aims to evaluate the effects of two biochar-compost-based amendments on the agronomic performance of cotton and economic feasibility in on-station and on-farm environments from three agro-ecological zones of northern Benin.

Materials and methods

Study sites

Two on-station experiments were carried in Northern Benin in the municipality of Parakou at the experimental station of Faculty of Agronomy/University of Parakou (9°18'04"N and 2°42'37"E) and in the municipality of Bembereke at the Agricultural Research Center of Northern Benin (9° 57′30"N and 2°43′39"E). The sites were located at agro-ecological zone III, Bembereke and agro-ecological zone V, Parakou). Two additional experiments were carried out on farmers' fields at Bembereke (village of Ina Gando, agro-ecological zone III; between 9°58'14" and 9°58'32"N and between 2°43'22" and 2°44'06"E) and Kandi (village of Padé, agro-ecological zone II, between 11°02'16" and 11°02'28"N and between 2°53'44" and 2°52'56"E). The sites (both on ation and on farm) were located in the Sudano-Savanna area of northern Benin (West Africa, Figure 1) with tropical climate characterized by a rainy season from May to October and a dry season from November to April. The average annual precipitations were 1,200, 1,070, and 1,000 mm in Parakou, Bembereke and Kandi, respectively. The soils in Parakou are of light texture and significant thickness due to the weakness of erosion. In Bembereke and Kandi, the soils are of tropical ferruginous type. These are soils with a more or less important depth and good permeability and porosity (Igué et al., 2017).

Experimental design, treatments and crop/soil management

For the on-station trials, the experimental design was a complete randomized block with ten (10) treatments and four replicates. The ten treatments were: (i) absolute control with no amendment (Ck), (ii) mineral fertilizer (MF) at 200 kg/ha, (iii) cow dung-based compost at 200kg/ha (CP1_200) and (iv) 300kg (CP1_300), (v) household waste-based compost at 200kg/ha (CP2_200) and (vi) 300kg (CP2_300), the combination of CP1 and 15%biochar designated Terra preta (TP) at 200kg/ha (vii, TP1_200) and at 300kg/ha (viii, TP1_300), the combination of CP2 and 15% biochar at 200kg/ha (ix, TP1_200) and 300kg/ha (x,TP1_300). The on-farm trials were conducted in two villages in the municipalities of Bembereke (village of Ina Gando) and Kandi (village of Padé) with four (04) farms per village. The experimental design was a randomized complete block with three replicates per farm with a total of 12 replicates per village. Each replicate consists of six (06) treatments selected from the 10 treatments tested in on-station trials namely: Ck, MF, CP1_200, CP2_200, TP1_200 and TP2_200.At both on-station and on-farm sites; each experimental plot (5 x 4 m) contained 6 separate lines with 80 cm row spacing and 40 cm spacing between plants. The blocks were separated by alleys of 3 m and the plots were separated by 2 m. Due to low application rates, and based on recent studies (Tovihoudji et al., 2017, 2019), the organic amendments were hill-placed to improve their effectiveness. The entire amount of compost and TP were applied after emergence (10–15 days after sowing, DAS). The mineral fertilizer was fractioned and spot-applied: 150 kg/ha of compound NPK at 10–15 DAS and 50 kg/ha of urea at 45 DAS. The cotton varieties recommended according to the agroecological zones were used: OKP 768 variety (150 maturity-days) in Parakou and Bemberekè and ANG 956 variety (150 maturity-days) in Kandi. Weeds were cleared by using a hand hoe at 14 and 45 DAS and the pesticide "Super Lambda" was sprayed 5-6 times to protect the cotton bolls against pests.

Participating farmers in the on-farm trials were identified by the agricultural advisors based on their experience in cotton production, their willingness and consent to participate in the trials. Farmers were trained before the start of the rainy season. They fully managed their experimentation, and the role of the researchers was limited to train them for application of amendments and monitoring management practices and also to data collection. Other crop management practices were left to each farmer. Organic and mineral fertilizers were applied in the same way as for the on-station trials.

Preparation of composts, biochar and Terra preta and their composition

CP1 compost was made by the *Association des Femmes Vaillantes et Actives* (AFVA) of Banikoara (northern Benin) by the windrow manufacturing method from dry cow dung, manure collected in stables, ash and rice straw. At maturity, CP1 compost was enriched with treated human urine. CP2 compost was made in piles (aerobic conditions) by the ReBin project from household organic waste in the municipality of Toffo (Southern Benin) and biogas digestates. The process took 3 months. Then, the compost was dried in shade, sieved and packaged in the bags of 50 kg.

Biochar was produced by slow pyrolysis using a metal drum kilns at a temperature of about 500 °C (Narzari et al., 2015; Steiner et al., 2018). Biochar was made from corn cobs. The biochar obtained after pyrolysis was crushed and powdered using a mill to ease the preparation of biochar-based-organic amendments.

Regarding the Terra preta, TP1 was produced by the AFVA. During the composting of CP1, at 2 months, the biochar was added to the windrows with 15% of biochar. The mixture lasted a month and was turned once a week to allow the nutrients to be loaded into the biochar. The biochar mixed with compost was sieved and then bagged into 50kg. TP2 was obtained from CP2. CP2 compost was purchased and mixed with biochar with 15% of biochar. An addition of water was regulary done and turned over every 4 days for 2 weeks.

In order to determine the chemical composition of the amendments, samples were collected, air-dried and oven-dried at 65°C to a constant mass before analysis. Each sample was a composite of ten to twelve subsamples. Subsamples of the dried materials were crushed for chemical analysis at the Laboratory of Soil, Water and Environmental Sciences (LSSEE/INRAB) at AgonkameyResearch Center, South Benin.

Sampling, measurements, and calculations

Initial soil analysis

Soil data were collected in both on-station and on-farm sites using the same methodology. At each site, samples were collected at a depth of 20 cm on the diagonal before the installation of the trials. After collection, the samples were carefully mixed to have a composite sample. The soil samples were spread, dried, crushed and sieved to 2 mm at the Soil, Water and Environmental Sciences Laboratory (LSSEE/INRAB) in Agonkanmey to determine particle size, organic carbon, total nitrogen, available phosphorus, exchangeable bases and cation exchange capacity. The particle size was determined by the Pipette Robinson method (AFNOR, 1987). Organic carbon was evaluated by the Walkley and Black (1934) method, total nitrogen was determined by the Kjeldahl method (Houba et al., 1995). Available phosphorus was determined by the Bray1 and Kurtz method (Van Reeuwijk, 1993), the cation exchange capacity by distillation and the exchangeable bases were determined by the Atomic Absorption Spectrophotometer after extraction with 1N ammonium acetate at pH by the method described by Van Reeuwijk (1993).

Yield and yield components

Plant height, number of vegetaive and reproductive branches and total bolls were recorded at boll opening stage on five plants randomly chosen per plot from each replicate. Cotton seed yield (kg/ha) was assessed two times by manually harvesting plants from each plot. The bolls were dried to ≤12% water content, ginned to determine cotton seed and lint yield. At the second harvest, one hundred (100) fully mature open bolls were hand-picked from each plot to determine single boll weight and ginning percentage. Lint percentage was calculated from the ratio of lint yield derived from 100 bolls and divided by seed cotton weight of 100 bolls.

Economic analysis

Economic profitability of the different treatments was analyzed based on gross return, gross margin, benefit/cost ratio (BCR) and value/cost ratio (VCR). Fixed costs included the cost of all major labor charges (field preparation, seeding, weeding and ridging) whereas variable costs included the cost of fertilizer and/or manure, cost of their transport and labor charges for the application of the fertilizer and/or manure (Table 1). The cotton seeds were not purchased because subsidized by the government through the "Société pour le Développement du Coton (SODECO). The prices of fertilizer fixed by SODECO were used. Labor costs for land preparation, sowing, fertilizer and/or manure application, weeding, and ridging were collected during the experiments through farm diaries. For the seed-cotton price, we used the average values of the two last seasons (265 FCFA kg^{-1}) (1USD=656 FCFA). Total revenue was calculated by multiplying cotton grain yield with the grain unit price. The gross margin (GM) was calculated by subtracting variable costs from total revenue. The gross return (GR) was calculated by subtracting the sum of the fixed and variable costs from the revenue. The value cost ratio (VCR) was computed as the difference in grain yield between the fertilized plots and the control plot multiplied by the unit market price of grain, divided by the cost of applied fertilizer. According to Kihara et al. (2015), general rules have been established for interpreting VCR. A VCR<1 indicates negative return on investment, a VCR = 1 entails positive return on investment bur not viable, whereas

TABLE 1 Inputs and outputs prices used in the economic analysis.

	Unit	Cost (USD)
Inputs		
Mineral Fertilizer	USD kg^{-1}	0.49
CP1	USD kg^{-1}	0.17
CP2	USD kg^{-1}	0.21
TP1	USD kg^{-1}	0.22
TP2	USD kg^{-1}	0.21
Labor for cotton cultivation		
Tillage	USD ha^{-1}	52.63
Seeding	USD ha^{-1}	17.54
Fertilizer transport	USD ha^{-1}	5.26–7.89
Fertilizer application	USD ha^{-1}	24.56
Weeding	USD ha^{-1}	21.92
Ridging	USD ha^{-1}	35.08
Output		
Cotton grain	USD kg^{-1}	0.46

TABLE 2 Chemical composition of the different organic amendments used.

	Biochar	Compost (CP1)	Compost (CP2)	Terra preta (TP1)	Terra preta (TP2)
Nitrogen (N), %	0.31	1.67	1.66	1.32	0.92
Phosphorus (P), %	0.28	0.04	0.07	0.04	0.07
Potassium (K), %	2.14	0.47	0.22	0.62	0.48
Calcium (Ca), %	1.10	1.56	1.34	1.07	1.33
Magnesium (Mg), %	0.16	0.37	0.25	0.34	0.26
Manganese (Mn), mg/kg	56.67	225.96	243.22	270.16	350.76
Zinc (Zn), mg/kg	118.00	39.21	99.30	39.66	93.02
Sodium (Na), mg/kg	961.28	-	-	-	-
pH water	10.21				
Ash, %	13.76	78.98	85.12	69.30	75.43
MS, %	89	70	77	72	77
Organic carbon, %	50.03	12.19	8.63	17.81	14.25

a VCR> or = 2 means positive return on investment that is economically viable.

Statistical analysis

Before analysis, the data were thoroughly cleaned. Then, the normal distribution and homogeneity of variances were checked with the Anderson-Darling and Levene's test, respectively. Regarding the on-station data, the effect of treatments and site-treatment interaction were examined using an analysis of variance (ANOVA 2) with Gensat v12 software. Because of the different varieties used in the on-farm trials, the statistical analyses were carried out for each site using a mixed linear model, considering treatments as a fixed factor and farms and replicates within farm as random factors. The test of Tukey was also used to compare means at 5%.

The stability of yields in relation to different environments was determined by the curve of the yield of treatments of a replicate as a function of the associated environmental yield (Guertal et al., 1994). The slope of the regression line was used to assess yield stability by treatment (smaller the slope, the greater is the yield stability; Guertal et al., 1994). The yield response of treatments relative to the control was calculated by subtracting the control yield from the treatment under consideration.

Results

Major characteristics of the amendments and experimental sites

Biochar had a pH of 10.21, with concentrations of 50.03% C, 0.31% total N, and 13.76% ash. The results of chemical analysis showed that the percentage of nitrogen of both types of compost is higher than the other organic amendments but low (0.31%) in the biochar. Unlike, the percentage of organic carbon is high (50.03%) in biochar and low in Toffo compost. By comparing the two Terra preta, it appears that the percentage of carbon contained in the Terra preta of banikoara (TP1) is higher (17.81%) than that contained in the Terra preta of toffo TP2) (Table 2). In addition, the percentage of phosphorus (0.28%) and potassium (2.14%) contained in the biochar is higher than the other treatments.

The texture of experimental soils at both on-station and on-farm sites varied from loamy sand to sandy loam. The nitrogen content of the sites where below 1% (Table 3). The soils were slightly acidic (pH = 5–6.6) both at on-station and on-farm sites. There was also a low level of total carbon. The values of available phosphorus were relatively high (Table 3).

A cumulative rainfall of 792.8 and 914.5 mm were recorded during the growing season in Bembereke and Parakou, respectively (Figure 2). In addition, the highest daily rainfall was recorded in the municipality of Parakou at 20 DAS (50 mm) which remains low compared to that recorded in Bembereke at 15 DAS (79 mm). Rainfall was well distributed in Parakou unlike Bembereke (Figure 2). Under on-farm experiments, Bembereke and Kandi received 868.4 mm and 881.3 mm of rain from June to October, respectively, with the highest amount of rain observed in August and September in Bemberekè and July and August in Kandi.

On-station trials

Growth parameters

The plant height was significantly affected by the different treatments at both sites ($P < 0.001$; Figure 3). The mineral fertilizer (MF) treatment produced the maximum height (132.85 cm). Among the organic treatments, the maximum height was obtained with TP1_200 (120.5 cm). There was a significant site by treatment interaction on plant height ($P <$

TABLE 3 Physico-chemical characteristics of the soil at experimental sites.

Soil and land characteristics	Unit	On-station		On-farm	
		Bembereke	Parakou	Bembereke	Kandi
pH_{H2O}	–	5.69	5.58	5.76 ± 0.17	5.68 ± 0.23
Total carbon	%	0.64	1.34	0.77 ± 0.06	0.95 ± 0.39
Total nitrogen	%	0.07	0.11	0.09 ± 0.01	0.08 ± 0.03
P-Bray1	mg $^{kg-1}$	26	66	15.88 ± 5.46	34.45 ± 6.57
Exch-K	$cmol^+ kg^{-1}$	–	–	0.21 ± 0.03	0.38 ± 0.30
Exch-Ca	$cmol^+ kg^{-1}$	–	–	1.90 ± 0.55	2.86 ± 2.38
Exch-mg	$cmol^+ kg^{-1}$	–	–	0.60 ± 0.11	0.82 ± 0.55
Exch-Na	$cmol^+ kg^{-1}$	–	–	0.16 ± 0.03	0.15 ± 0.04
Sand	%	87	78	81 ± 8	76 ± 5
Silt	%	9	12	14 ± 0.3	15 ± 5
Clay	%	4	10	5 ± 3.7	8 ± 3
Textural class		Loamy sand	Sandy loam	Loamy sand	Loamy sand
Seasonal rainfall					
June	mm	103.9	142	103.9	92
July	mm	175.3	270	175.3	219.5
August	mm	234.4	137	234.4	256.9
September	mm	250.3	231	250.3	182.8
October	mm	104.5	203.5	104.5	130.1

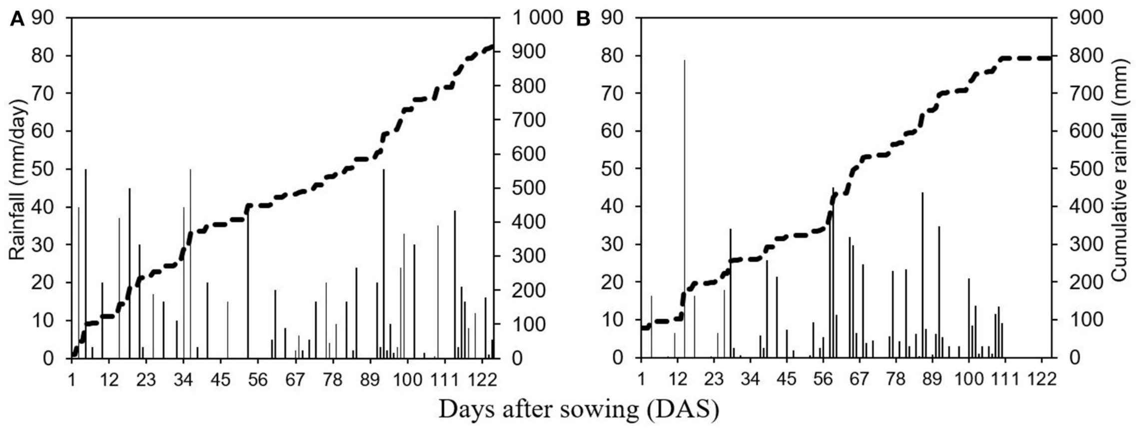

FIGURE 2
Rainfall distribution under on-station experiments: **(A)** Parakou and **(B)** Bembereke.

0.001). Indeed, for organic fertilizers, the average height values were higher in Parakou than in Bembereke for all treatments with a maximum height of 138.6 cm.

The number of vegetative branches was significantly affected by the sites and treatments ($P < 0.001$; Figure 3) with the largest number of vegetative branches recorded at Bembereke. Biochar-based fertilizers with compost at 200 kg/ha (TP2) recorded the largest number of vegetative branches compared to the control (2 branches). A significant site by treatment interaction was observed ($P < 0.001$). At Bembereke, the highest number of vegetative branches was observed in the MF treatment followed by CP2_300, while in Parakou it was observed in TP1_200 followed by CP1_200.

The number of fruiting branches was significantly affected by the sites and treatments ($P < 0.001$; Figure 3) with the highest number recorded in Parakou and underin CP1_200 (16 branches), TP1_300 (15 branches) and MF (15 branches) treatments. There was also a significant site by treatment

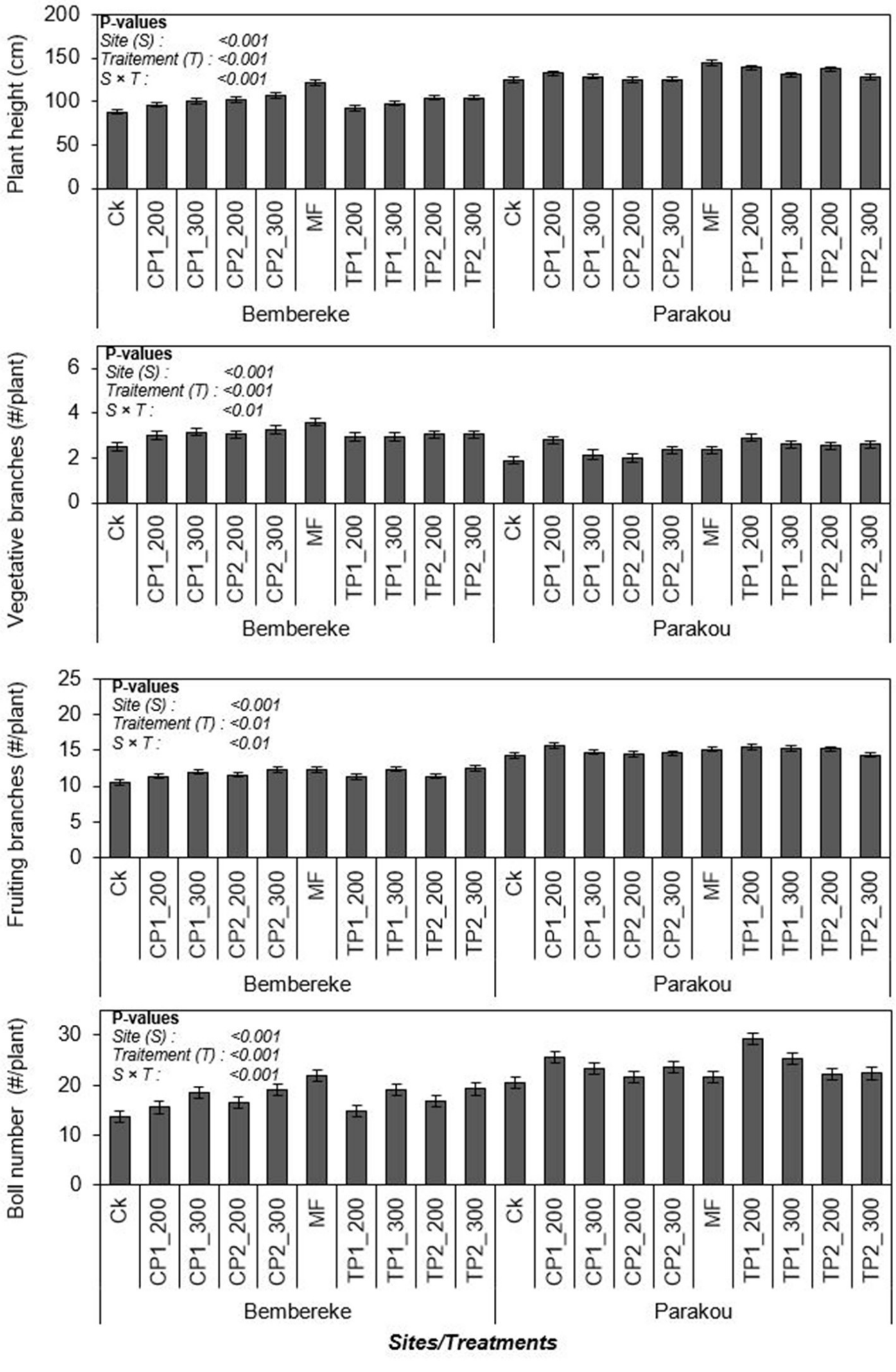

FIGURE 3
Site by treatment interaction effect on plant height, number of vegetative and fruiting branches, and number of bolls of cotton. Ck, control; MF, mineral fertilizer; CP1-200, Compost of Banikoara at 200 kg/ha; CP1-300, Compost of Banikoara at 300 kg/ha; CP2-200, Compost of Toffo at 200 kg/ha; CP2-300, Compost of Toffo at 300 kg/ha; TP1_200, Terra preta of Banikoara at 200 kg/ha; TP1_300, Terra preta of Banikoara at 300 kg/ha; TP2_200, Terra preta of Toffo at 200 kg/ha; TP2_300, Terra preta of Toffo at 300 kg/ha.

interaction. CP1_200 produced the highest fruiting branches (16 branches) in Parakou while TP2_300 produced the highest fruiting branches (13 branches) in Bembereke.

The number of bolls per plant varied significantly between sites ($P < 0.001$; Figure 3) with the highest number recorded in Parakou. The number of bolls per plant were significantly

TABLE 4 Effect of different biochar-based amendments on seed-cotton and lint yields at the two on-station experimental sites in northern Benin.

Factors		Seed-cotton yield (t/ha)	Lint yield (t/ha)
Station	Bembereke	2.00	1.08
	Parakou	2.04	1.14
	SE	0.052	0.032
Treatments	Ck	1.36[a]	0.79[a]
	MF	3.03[f]	1.66[d]
	CP1-200	1.64[abc]	0.92[ab]
	CP1-300	2.12[cde]	1.19[bc]
	CP2-200	1.51[ab]	0.83[a]
	CP2-300	1.78[abcd]	0.97[ab]
	TP1-200	1.90[bcde]	1.08[abc]
	TP1-300	2.53[ef]	1.37[cd]
	TP2-200	2.00[bcde]	1.06[abc]
	TP2-300	2.21[de]	1.20[bc]
	SE	0.117	0.071
P-values	Site (S)	0.565	0.197
	Treatment (T)	<0.001	<0.001
	S x T	0.922	0.908

Ck, control; MF, mineral fertilizer; CP1-200, Compost of Banikoara at 200 kg/ha; CP1-300, Compost of Banikoara at 300 kg/ha; CP2-200, Compost of Toffo at 200 kg/ha; CP2-300, Compost of Toffo at 300 kg/ha; TP1_200, Terra preta of Banikoara at 200 kg/ha; TP1_300, Terra preta of Banikoara at 300 kg/ha; TP2_200, Terra preta of Toffo at 200 kg/ha; TP2_300, Terra preta of Toffo at 300 kg/ha. Average values with the same letters are not significantly different at 5%, test of Tukey. SE, standard error.

affected by the treatments. At 120 DAS, the highest number of bolls per plant (22 bolls) were recorded in the TP1_300 and MF treatments. There was also a significant site by treatment interaction on the number of bolls per plant. In Parakou, the highest number of bolls per plant was recorded in TP1_200 (29 bolls) while the highest number of capsules per plant was determined with MF in Bembereke (22 bolls).

Yield and components

The seed-cotton and lint yields were not affected by sites but were significanlty affected by treatments ($p < 0.05$; Table 4). The MF treatment produced the highest yields in term of seed-cotton and lint (3.0 and 1.7 t/ha, respectively). Among the organic fertilizers, the TP1_300 treatment produced a similar seed and lint yields compared to the MF treatment with an 86 and 73% increase over the control, respectively. No site by treatment interaction was observed for the seed-cotton and lint yields (Table 4).

Economic indicators

All the economics parameters were significanlty affected by the sites ($p < 0.001$; Table 5). The site of Parakou produced the highest values of net return (NT), gross margin (GM), BCR and VCR. NT, GM, BCR and VCR were also significanlty affected by treatments ($p < 0.01$; Table 5). The MF treatment produced the highest values for these economics parameters

TABLE 5 Effect of different biochar-based amendments on economic indicators at the two on-station experimental sites in northern Benin.

Factors	Levels	Net return (USD/ha)	Gross margin (USD/ha)	BCR (–)	VCR (–)
Station	Bembereke	224.01	334.52	1.24	1.83
	Parakou	644.44	754.96	3.59	3.63
	SE	16.78	16.78	0.09	0.25
Treatments	Ck	304.33[a]	414.84[a]	–	–
	MF	683.4[c]	793.91[c]	3.08[b]	4.41[b]
	CP1-200	329.56[a]	440.08[a]	1.97[a]	1.45[a]
	CP1-300	458.97[ab]	569.48[ab]	2.49[ab]	3.09[ab]
	CP2-200	321.19[a]	431.70[a]	1.86[a]	1.27[a]
	CP2-300	425.16[ab]	535.68[ab]	2.20[ab]	2.45[ab]
	TP1-200	387.98[ab]	498.49[ab]	2.20[ab]	2.28[ab]
	TP1-300	513.73[bc]	624.25[bc]	2.59[ab]	3.39[ab]
	TP2-200	439.87[ab]	550.39[ab]	2.54[ab]	3.17[ab]
	TP2-300	478.05[ab]	588.57[ab]	2.47[ab]	3.09[ab]
	SE	37.51	37.51	0.20	0.53
P-values	Site(s)	<0.001	<0.001	<0.001	<0.001
	Treatment (T)	<0.001	<0.001	0.002	0.002
	S x T	<0.001	<0.001	0.002	0.003

Ck, control; MF, mineral fertilizer; CP1-200, Compost of Banikoara at 200 kg/ha; CP1-300, Compost of Banikoara at 300 kg/ha; CP2-200, Compost of Toffo at 200 kg/ha; CP2-300, Compost of Toffo at 300 kg/ha; TP1_200, Terra preta of Banikoara at 200 kg/ha; TP1_300, Terra preta of Banikoara at 300 kg/ha; TP2_200, Terra preta of Toffo at 200 kg/ha; TP2_300, Terra preta of Toffo at 300 kg/ha. Average values with the same letters are not significantly different at 5%, test of Tukey. SE, standard error.

TABLE 6 Effect of biochar-based amendments on seed-cotton and lint yields at two on-farm experimental sites in northern Benin.

	Bembereke			Kandi		
	Total yield (t/ha)	Lint yield (t/ha)	Response (%)	Total yield (t/ha)	Lint yield (t/ha)	Response (%)
Ck	0.80[a]	0.29[a]		0.75[a]	0.28[a]	
MF	1.97[d]	0.71[c]	162.07[b]	1.92[c]	0.68[c]	163.58[b]
CP1-200	1.24[bc]	0.57[bc]	64.63[a]	1.22[b]	0.43[b]	66.62[a]
CP2-200	1.10[ab]	0.51[b]	44.37[a]	1.15[b]	0.40[b]	57.62[a]
TP1-200	1.49[c]	0.63[bc]	99.00[ab]	1.42[b]	0.49[b]	91.96[a]
TP2-200	1.35[bc]	0.49[b]	74.55[a]	1.23[b]	0.43[b]	69.93[a]
SE	0.076	0.034	16.292	0.066	0.026	15.599
P-values	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Ck, control; MF, mineral fertilizer; CP1-200, Compost of Banikoara at 200 kg/ha; CP2-200, Compost of Toffo at 200 kg/ha; CP2-300, Compost of Toffo at 300 kg/ha; TP1_200, Terra preta of Banikoara at 200 kg/ha; TP2_200, Terra preta of Toffo at 200 kg/ha. Average values with the same letters are not significantly different at 5%, test of Tukey. SE, standard error.

TABLE 7 Effect of biochar-based amendments on economic indicators at two on-farm experimental sites in northern Benin.

	Bembereke				Kandi			
	Net return (USD/ha)	Gross margin (USD/ha)	BCR (-)	VCR (-)	Net return (USD/ha)	Gross margin (USD/ha)	BCR (–)	VCR (–)
Ck	100.58[a]	322.38[a]	-	-	109.40[a]	303.76[a]	-	-
MF	573.73[d]	684.25[d]	2.59[b]	4.25[b]	554.86[c]	665.38[c]	2.50[b]	4.25
CP1-200	304.60[bc]	442.56[abc]	1.99[ab]	3.13[ab]	269.21[b]	434.61[b]	1.94[ab]	3.32
CP2-200	221.14[ab]	380.44[ab]	1.56[a]	1.93[a]	255.28[b]	400.86[ab]	1.68[a]	2.55
TP1-200	381.19[c]	537.44[c]	2.42[b]	4.28[b]	364.82[b]	507.35[b]	2.25[ab]	4.11
TP2-200	322.94[bc]	482.24[bc]	2.15[ab]	3.56[ab]	276.58[b]	435.88[b]	1.88[ab]	3.11
SE	30.19	30.56	0.19	0.45	27.03	26.83	0.16	0.52
P-values	<0.001	<0.001	0.006	0.004	<0.001	<0.001	0.005	0.136

Ck, control; MF, mineral fertilizer; CP1-200, Compost of Banikoara at 200 kg/ha; CP2-200, Compost of Toffo at 200 kg/ha; CP2-300, Compost of Toffo at 300 kg/ha; TP1_200, Terra preta of Banikoara at 200 kg/ha; TP2_200, Terra preta of Toffo at 200 kg/ha. Average values with the same letters are not significantly different at 5%, test of Tukey. SE, standard error.

(683.4 USD/ha, 793.9 USD/ha, 3.1 and 4.4, respectively). Among the organic fertilizers, the TP1_300 treatment produced the highest values for NT, GM, BCR and VCR (513.7 USD, 624.3 USD, 2.6 and 3.4, respectively) similar to the values obtained with MF treatment. A significant interaction were observed between site and treatment for all economics parameters ($p < 0.01$; Table 5). The response to treatments was more pronounced in Parakou than in Bembereke.

On-farm trials

Yield and components

In the on-farm sites, seed-cotton and lint yields were significantly affected by the treatments at both study sites ($P < 0.001$; Table 6). At both sites, the TP1_200 produced good yield in term of seed-cotton and lint which was close to the MF treatment with an increase of 99 and 92% in seed-cotton yield compared to the control, in Bembereke and Kandi, respectively (Table 6).

Economic indicators

Net return (NT) and gross margin (GM) were significanlty affected by the treatments ($p < 0.001$; Table 7) in Bembereke and Kandi. The MF treatment produced the highest NT and GM (573.73 and 554.86 USD/ha, and 684.25 and 665.38 USD/ha in Bembereke and Kandi, respectively). Among the organic fertilizers, the TP1_200 treatment produced the highest values for NT and GM (381.19 and 364.82 USD/ha, and 537.44 and 507.35 USD/ha in Bembereke and Kandi, respectively). The TP1_200 treatment produced BCR and VCR values most closed to the MF treatment at both sites.

Analysis of environment stability and response to amendments

The stability analysis showed that TP1_200 performs well in all environments (Figure 4A). Treatments such as CP1_200, TP1_200 and TP2_200 have intermediate responses in all environments while mineral fertilizer (MF) treatment was more sensitive to improving environmental

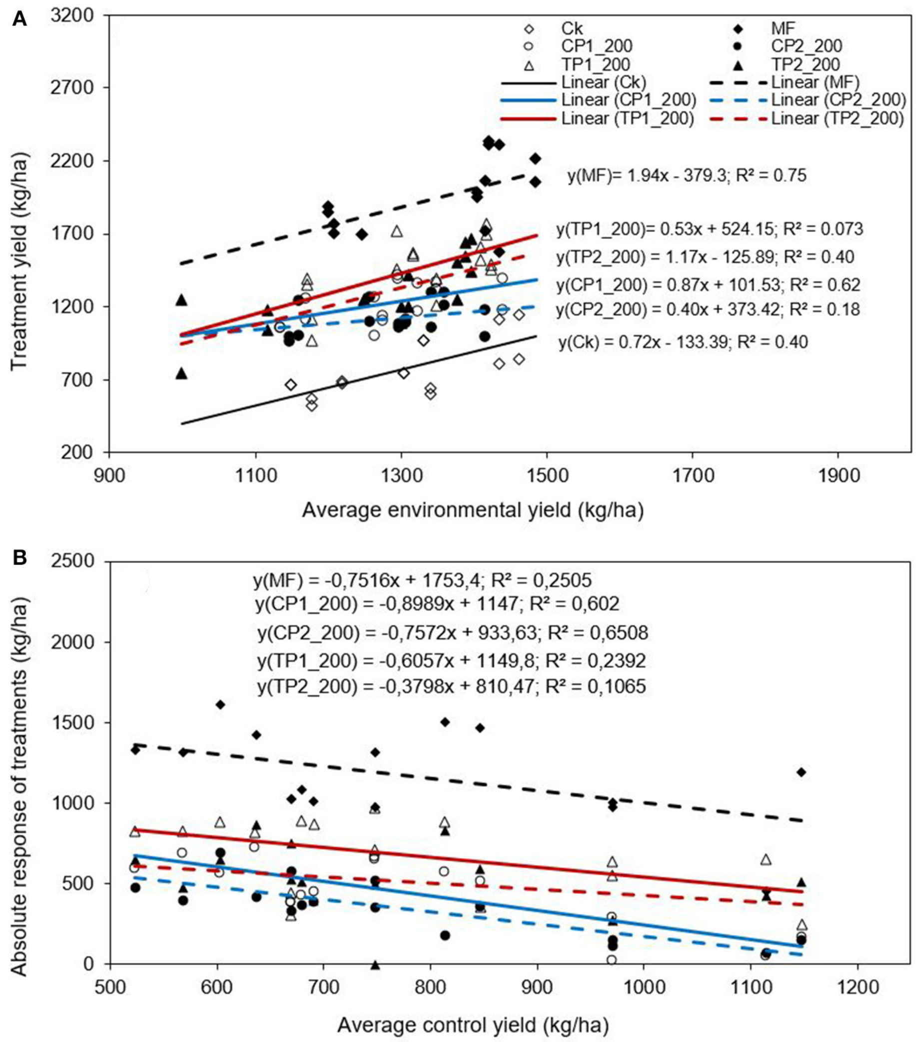

FIGURE 4
Stability analysis **(A)** and absolute response of different treatments as a function of the yield of the control plot **(B)**. 4 The environmental average is the average yield of all treatments on a given agricultural site; Ck, control; MF, mineral fertilizer; CP1-200, Compost of Banikoara at 200 kg/ha; CP2-200, Compost of Toffo at 200 kg/ha; CP2-300, Compost of Toffo at 300 kg/ha; TP1_200, Terra preta of Banikoara at 200 kg/ha; TP2_200, Terra preta of Toffo at 200 kg/ha.

conditions. Nevertheless, it should be noted that the slope under the CP1_200 and CP2_200 treatments remain low, resulting in more stable yields. On the other hand, the slope under the MF treatment was strong which makes it more unstable.

Figure 4B shows the absolute responses of the different treatments as a function of the yield of the control plot. Responses vary considerably from 461 to 1612 kg/ha, 29 to 721 kg/ha and 0 to 975 kg/ha, for MF, CP and TP treatments at both sites, respectively (Figure 4B). The yield response of different treatments tends to decrease with increased yields in control plots, with lesser decrease in TP treatments.

Discussion

Effect of treatments on cotton growth parameters

From this study, it appears that the different biochar-based treatments improved the growth of cotton with TP1 treatment producing better results at both on-station and on-farm trials. Compared to other treatments, the application of MF yielded best. This is explained by the solubility and availability of nutrients in MF that would have promoted the rapid growth of plants unlike the biochar and compost-based amendments (Kouassi et al., 2019). These results are similar to those obtained by Elangovan and Sekaran (2014) who showed that the increase in height of cotton plants was due to the balanced effect of the mineral fertilizer. The latter were able to show that biochar amendments increase total nitrogen by 7% and organic carbon by up to 69%. Using mass balance analysis, they observed no detectable loss of C from biochar during incubations, but recovered <20% of C from manure. In addition, this difference in performance may also be due to the slow decomposition of biochar-based amendments after incorporation into the soil (Fischer and Glaser, 2012; Jien et al., 2015; Koulibaly et al., 2015).

Among the various biochar-based amendments, compost at 200 kg/ha and Terra preta at 200 kg/ha produced better growth preferences in on-station and on-farm conditions, respectively. Terra preta applied at 300 kg/ha was more productive in terms of the number of vegetative and fruiting branches and number of bolls. The stability that biochar confers on the compost contained in Terra preta justifies the advantage observed with Terra preta compared to sole compost and in particular with Terra preta of Banikoara (Fischer and Glaser, 2012; Jien et al., 2015; Zhang et al., 2020). The better performance of the Terra preta of Banikoara (TP1) compared to that of Toffo (TP2) could be explained by its richer chemical composition (Table 1) and by a possible fast decomposition process than TP2.

Effect of treatments on cotton yield and economic profitability

Regardless of the experimental conditions of each farm, we observed that yields increased by 96 and 73% on average, for the TP1 and TP2 treatments, respectively, compared to the control. The combination of compost and biochar (Terra preta) provides greater stability to soil nutrients and better water use for plants (Pandit et al., 2019). It is therefore understandable that the best performances demonstrated by Terra preta (TP1 and TP2) compared to the application of composts alone are related to the combined action of biochar and compost. Indeed, compost is a natural source of nutrients needed by plants for growth and productivity. Biochar is generally nutrient poor (Ding et al., 2016) but very porous in nature with a high specific surface area (Palansooriya et al., 2019), giving it a great potential to retain nutrients. According to Rees (2014), biochar controls nutrient mobility in soil-plant systems through a series of different mechanisms and on a practical level, it promotes phytostabilization and phytoextraction strategies of nutrients in soils. Several studies have reported the effect of compost combined with biochar (Terra preta) on plants. Rombel et al. (2022), noted that the application of biochar combined with compost, as the case of Terra preta in our study, is better than the separate application of biochar and compost, demonstrating the synergistic and beneficial effect of biochar mixed with compost. Although the nutrient content of Terra preta depends on the raw materials of the compost and biochar, the pyrolysis and the environmental conditions during the composting process (Antonangelo et al., 2021), the studies of Oldfield et al. (2018), confirmed that the mixed application of compost and biochar to the soil was beneficial to the crops with a lower negative environmental impact than the use of synthetic mineral fertilizers alone. According to Sánchez-Monedero et al. (2019), the mixed application of compost and biochar to the soil can not only serve as a substitute for synthetic mineral fertilizers, but it also stimulates microbial life in the soil, which in turn contributes to soil nutrient cycling. Several mechanisms have been suggested to explain the plant yield response to mixing biochar with a nutrient source. These include optimization of plant nutrient availability (Agegnehu et al., 2016), increased soil microbial biomass and activity (Wang et al., 2016), and most importantly the liming effect (Kätterer et al., 2019; Wang et al., 2019).

The differences in yields obtained between the fields at the station (Table 4) and at the farm (Table 6) can be explained by the texture of the soils at the sites, their initial level of fertility, and the rainfall. Indeed, the farmer's fields and station of Bembereke have the same soil texture (Loamy sand) with almost the same level of nitrogen, whereas the Parakou station has a sandytexture (Sandy loam) with a higher level of nitrogen. In addition, unlike the station of Parakou, there is low rainfall with an irregular distribution at Bembereke and Kandi. Sultan et al. (2010) and Anwar et al. (2020) also showed in their studies that cotton yield can vary greatly depending on rainfall and its distribution. Wang et al. (2019) reported that the effect of combining biochar with compost on plants is more noticeable on sandy soils or when there are drought spells during growing season. For example, Glaser et al. (2015) showed that combining biochar with compost increased maize yield by 26% over compost when grown on sandy soil. Similarly, Głab et al. (2018) found that the application of the compost-biochar mixture on sandy soils exhibited better water retention than the application of compost without biochar. Mekuria et al. (2014) showed that during a drought period, soils where the compost-biochar mixture was applied exhibited a smaller reduction in grain yield (35-36%) compared to soils that received only compost (40–64%). Furthermore, the initial soil fertility level influences the plant response to the compost-biochar mixture application (Wang et al., 2019).

The results of stability and response analysis showed a huge variability in yields between farms and within the same treatment (Figure 4B). Indeed, the treatment TP1_200 has been much more adapted and stable to the environment in which the trials were carried out. This could be due to its chemical composition which despite the poverty of the soils provides the necessary elements for the growth of cotton seedlings. Several authors have also observed a high variability in responses to organic and/or mineral fertilization for various crops and environments (Bielders and Gérard, 2015; Tovihoudji et al., 2019).

From an economic point of view, all treatments led to mean VCR values >2 (Tables 5, 7), which is generally considered as the lower threshold for adoption in smallholder, risk-averse farming systems. Hence all tested biochar-compost-based amendments may appear suitable for the conditions of northern Benin. Nevertheless, mean BCR and VCR values were notably higher for treatments involving CP1 (i.e CP1 and TP1) compared to those involving CP2. This is a direct consequence of the fact that CP1 and TP1 perform better than CP2 and TP2. Applying mineral fertilizer alone, though economically viable than the tested biochar-compost-based amendments, should not be suggested in the long-term. Continuous cultivation without organic amendment has been shown to lead to an increase of soil acidification and an overall decline in soil organic matter content and in the availability of other nutrients (Adams et al., 2016). Organic amendments are essential for sustaining soil quality in the long run. In addition to micronutrients supply, organic amendments are also essential to sustain soil life (Agegnehu et al., 2016). Hence, spot application of biochar-compost-based amendments (particularly TP1) appears to be an economically good alternative in the current agroecological transition pathway.

Conclusions

The results of the current study show that growth and yields of cotton can be significantly improved by biochar-compost-based amendments and ultimately farmers' livelihoods. From an economic pointview, TP1 treatment (at 200 or 300 ka/ha) appears interesting. Although higher agronomic and economic effects were observed for MF treatment, applying mineral fertilizer alone may prove unsustainable in the current context. Therefore, farmers should be encouraged to substitute mineral fertilizer by biochar-compost-based amendments by valuing the increased animal and crop wastes production as biochar and compost. However, actions have to be taken to provide farmers with more financial supports and training to produce biochar and compost. The results of stability and response analysis showed a variability in yields between farms and within the same treatment. The treatment TP1_200 was much more adapted and stable to various environments. However, further studies are needed across other agroecological zones in Benin and over several production seasons to better understand the agronomic response.

Data availability statement

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

Author contributions

GT and RD: conceptualization, methodology, and writing—review and editing. GT, WA, and FA: investigation, analysis, and writing—original draft. WA and TG: funding acquisition and review. 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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Short-term trade-offs of organic matter management strategies for smallholder farms

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Organic matter management (OMM) strategies such as farmyard manure (FYM) application, legume integration, crop residue incorporation, and alley cropping are recognized for improving soil fertility and crop productivity. However, studies on yield and economics of a combination of such strategies on smallholder farms are generally scarce, yet an understanding of such can enhance adoption. This study analyzed the yield and gross margins of crops grown with OMM strategies in comparison to those grown under inorganic fertilizer application on smallholder farms. Field experiments with five treatments over two short rainy (SR) and two long rainy (LR) seasons were conducted from January 2018 to February 2020 on 10 smallholder farms. The treatments (T) included T1 (control): the inorganic fertilizer application strategy that involved maize monocrop with 50 kg/ha Diammonium phosphate (DAP) application and the OMM strategies (T2-T5). T2: cowpea-maize-bean-maize rotation; T3: cowpea-maize-bean-maize rotation + 2.5 tons/ha FYM; T4: *Faidherbia albida* alleys + cowpea-maize-bean-maize rotation; and T5: *Faidherbia albida* alleys + cowpea-maize-bean-maize rotation + 2.5 tons/ha FYM. The maize in T3-T5 was intercropped with *Mucuna pruriens*. The results indicate that the grain and residue yields in LR were not significantly different among all treatments. The total variable costs, which included monetarized labor and annualized capital costs for the establishment of *F. albida* were significantly higher under T1 than in T2-T5 during LR2018 and not significantly different from what was observed under T3-T5 in LR2019. The accumulated revenues and gross margins for the four seasons were not significantly different between T1 and the OMM strategies. We conclude that the integration of OMM strategies can give gross margins similar to the 50 kg/ha DAP application. Further, based on the price sensitivity analysis, we conclude that the smallholder farmers could adopt T3 and T4 as the gross margins under these treatments are less affected by grain price fluctuations than in T1, T2, and T5. Since the smallholder farmers can access the planting materials, we recommend the adoption of T3 and T4 on smallholder farms.

KEYWORDS

alley cropping, annualized capital costs, *Faidherbia albida*, farmyard manure, gross margins, labor costs, *Mucuna pruriens*, organic matter management

Introduction

Agriculture in Uganda, where 95 percent of the farmers are smallholders with landholdings averaging two hectares, is characterized by low land productivity (Njeru et al., 2016). Taking an example of maize, which is one of the most important crops grown for food and sale in Uganda (Agona et al., 2001), its productivity in terms of grain yield has been recorded at 1.5 tons/ha compared to the potential of 7 tons/ha (Okoboi et al., 2012; Simtowe et al., 2019). One of the major factors contributing to these low crop yields is the lack of adequate nutrients for crops resulting from soil nutrient depletion (Tadele, 2017), low recirculation of animal manure, low share of legumes, lack of crop residue (straw) management, and low mineral fertilizer application regimes (Odhiambo and Mag, 2008). Soil nutrient depletion emanates from a complex of different non-adapted farming practices including continuous cropping without nutrient input, as well as farmers carrying away crop residues from the fields for feeding livestock without recycling nutrients through farmyard manure (FYM) application (Nkonya et al., 2005; Ronner and Giller, 2013; Tadele, 2017). The productivity is worsened by the reliance of farmers on the natural fertility of the soil since they lack mineral fertilizers and if applied, they are washed out by surface runoff (Woniala and Nyombi, 2014). The low transfer rates of mineral fertilizer nutrients to the crops (nutrient availability) as a result of soil compaction, reduced root growth, negative humus balances, low water holding capacity, and leaching processes (Tadesse et al., 2013; Massah and Azadegan, 2016), can force the farmers to abandon mineral fertilizer application. There is a knowledge gap on how to increase synthetic fertilizer uptake, i.e., productivity *via* other management strategies. Other reasons for the reliance of farmers on natural soil fertility include the prohibitive prices and limited accessibility of mineral fertilizers by farmers located in remote areas (Nziguheba et al., 2016).

Although trade-offs with family income due to costs of acquisition, transport, and application of organic matter management (OMM) strategies like vermicompost have been reported (Flores-Sánchez et al., 2015), other OMM strategies such as FYM application, alley cropping, forage & grain legume integration, and crop residue incorporation on arable land have been documented for increasing soil characteristics. These soil characteristics include soil carbon, soil water-holding capacity, nutrient storage and availability (Birhane et al., 2018; Beuschel et al., 2019; Bu et al., 2020). In addition, the application of OMM strategies reduces soil compaction and increases crop productivity (Lupwayi et al., 2011; Akmal et al., 2015; Birhane et al., 2018; Beuschel et al., 2019; Bu et al., 2020). Organic matter management therefore, to a certain degree reduces the dependency on mineral fertilizers but also acts as a precondition for optimal utilization and uptake of nutrients by plants (De Moura et al., 2010; Pirhofer-Walzl et al., 2012). The multiple functions OMM contributes to ecosystem services cannot be delivered by commercial mineral fertilizers (Mikha et al., 2017). Moreover, the application of OMM strategies requires less finance (cash) compared to the inorganic mineral fertilizers and the inputs are readily available to most farmers. In contrast to mineral fertilizers, the diverse OMM strategies offer several benefits:

- If forage and alley legume trees such as *Faidherbia albida* are integrated into the farming system, nitrogen demand can be covered as the trees can contribute about 80.2 kg N/ha/season when they are mature. This is about the recommended average application rate of mineral nitrogen fertilizer for maize production in Uganda (Mugendi et al., 1999; Sunday and Ocen, 2015; Yengwe et al., 2018; Kohler, 2020; Silva-Galicia et al., 2020).
- Organic matter from decomposed biomass protects nutrients against leaching, feeds microorganisms, stores nutrients, and increases their availability (Yang et al., 2018).
- Specifically, forage and alley legume trees with their deep rooting system can uptake nutrients from the subsoil, and transfer them into the main rooting zone, enriching the nutrient concentration (De Moura et al., 2010; Pirhofer-Walzl et al., 2012). This vertical (re-)transfer of the farm nutrient cycle of probably leached nutrients is not an addition of nutrients *per se*, but an enrichment of soil stock nutrients in the upper layer.
- Organic matter includes not only one or two nutrients, as is usually the case when applying mineral fertilizer, but a broad range of macro and micronutrients that are offered to the soil and crop in a more or less available form.

It should be noted that all nutrients in the biomass are from the soil's nutrient stock if no deposition, mineral fertilizer, organic manure, or forage are added from outside of the farm, except nitrogen, which also results from natural fixation processes.

Although several OMM strategies have been applied to improve soil fertility (Cai et al., 2019; Sánchez-Navarro et al., 2019; Vanlauwe et al., 2019), their systematic and comprehensive application is still an exception, and soil nutrient depletion and low crop productivity have persisted (Woniala and Nyombi, 2014). The reason for the low adoption rate of the OMM strategies such as tillage systems could be related to their high labor requirements (Dahlin and Rusinamhodzi, 2019), and the limited knowledge about the positive impact on yield and economics (costs, revenues, and profits). This could specifically be the case if more than two strategies (for example the application of grain and forage legumes, alley trees, and FYM) are jointly applied. While the positive influence of single OMM strategies is well known and studied (Akmal et al., 2015; Yengwe et al., 2018; Bu et al., 2020), literature on the impact of combined OMM strategies on yield and economic parameters is limited. Moreover, training and advisory services have not been sufficient in extending related information to farmers (Sebaggala and Matovu, 2020). This study tested the effects of combined OMM strategies such as alley cropping, FYM application, as well as grain and forage legume integration compared to inorganic fertilizer application strategy on (a) crop yield, (b) costs and (c) gross margins. This study hypothesizes that the application of OMM strategies would (1) increase crop yield to amounts equal to the inorganic fertilizer application strategy; (2) reduce costs compared to the inorganic fertilizer application strategy; (3) yield gross margins that are comparable to the ones obtained through the inorganic fertilizer application strategy.

Materials and methods

This study applied a systems perspective that involved both natural science and economic perspectives. The first part of this section describes the study area and the field trials including the experimental design, choice of crops, and sampling procedure. This section was adapted from the methodology developed by Ekyaligonza et al. (2022). The second part of this section is the economic analysis of the different OMM strategies (treatments) over four crop-growing seasons in 2018 and 2019.

Study area

A field experiment was conducted on 10 randomly selected farmer fields that are located in Nyabbani Sub-county of Kamwenge district (00°11.17′ N, 30°27.07′ E, 1160 m a.s.l.) in the Rwenzori region of Uganda (Figure 1). The study area experiences a tropical climate with an annual temperature range of 20-25° C and annual rainfall of 700-1,400 mm with a short rainy season (SR) from March to May and a long rainy season (LR) from August to November (FAO, 2005). In 2018, the study area received a total of 524.8 mm of rain in SR and 657.2 mm in LR, while in 2019, a total of 385.6 mm of rain was received in the SR and 578.9 mm in LR (Figure 2). Any possible differences between sites due to climatic conditions were taken care of by the randomization and replication effect of the experimental design. The soils were dominantly sandy clay loamy acrisols (about 57% sand, 19% silt, and 24% clay in the topsoil) and were acidic with a pH (H_2O) of approx. 5.1, a cation exchange capacity (CEC) of 5 $cmol_c$/kg, low organic carbon of 0.8%, and bulk density of 1.41 kg/dm^3 (FAO, 2012). Such soils require adjustment of pH and organic matter management to increase water holding capacity and plant nutrient uptake.

Field experiments

Experimental design, treatments, and sampling

Field experiments were conducted for 2 years from January 2018 until February 2020 in four consecutive crop-growing seasons: two for SR and another two for LR. The trials were established on 10 smallholder farms and the owners of the farms fully participated in carrying out all the relevant agronomic practices. A randomized complete block design (RCBD) was established, where each farm was considered a block ($n = 10$). Five treatments were randomly allocated per block. The five treatments (T1-T5) included:

- T1: maize monocrop with Diammonium phosphate (DAP) fertilizer (18-46-0) at an application rate of 50 kg/ha (N: 9 kg/ha; P_2O_5: 10.05 kg/ha), a rate affordable to most maize subsistence farmers in the Rwenzori. This was treated as control as it is a common practice to use low doses of fertilizers among the majority of the smallholder maize farmers in the Rwenzori region;
- T2: Cowpea-maize-beans-maize rotation. The initial plan was to rotate cowpea with maize but the farmers opted for beans in the SR2019 following the low cowpea yields realized during SR2018;
- T3: Cowpea-maize/*Mucuna pruriens*-beans-maize/*Mucuna pruriens* rotation + farmyard manure (FYM) from cattle containing N: 13 kg/ha; P: 6 kg/ha; K: 18 kg/ha. The FYM was applied at an application rate of 2.5 tons/ha as fresh matter, which is the feasible amount that can be produced by most smallholder farmers in the Rwenzori region;
- T4: Cowpea-maize/*Mucuna pruriens*-beans-maize/*Mucuna pruriens* rotation + *Faidherbia albida* alleys;
- T5 Cowpea-maize/*Mucuna pruriens*-beans-maize/*Mucuna pruriens* rotation + FYM + *F. albida* alleys (see Table 1 for the detailed description of the treatments).

For each farm, the five treatments were allocated to five plots with dimensions of 10 m x 10 m each. These plots were separated by 0.5 m walkways. The plots were tilled with a hand hoe and then seeds of selected crops were sown. Selection of crops and varieties was done according to the following criteria: (i) Maize (*Zea mays*) was selected because it is one of the major staple foods for the majority of the population in East Africa and it is cropped for both food and cash (Agona et al., 2001). In this study, maize variety *Longe 5* at a rate of 24.7 kg/ha was selected because of its high share of protein and its drought tolerance (FAO, 2017). This maize variety matured 115 days after sowing; (ii) The legume cowpea (*Vigna unguiculata*) produces high biomass and nitrogen in a short time and is known for its high pre-crop value (Omae et al., 2014). The grains and leaves of cowpeas are served as food to some tribes

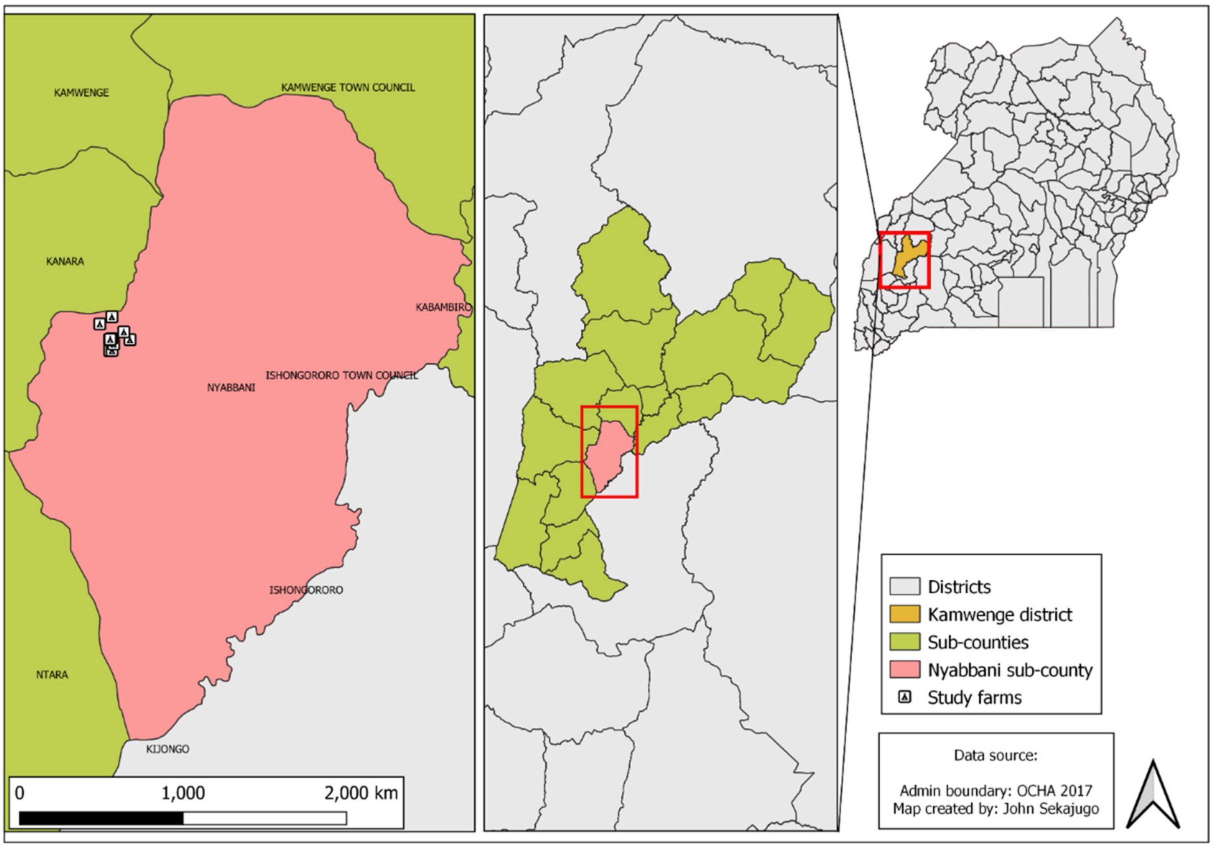

FIGURE 1
Location of the study farms in Kamwenge district, Uganda. Source Ekyaligonza et al. (2022).

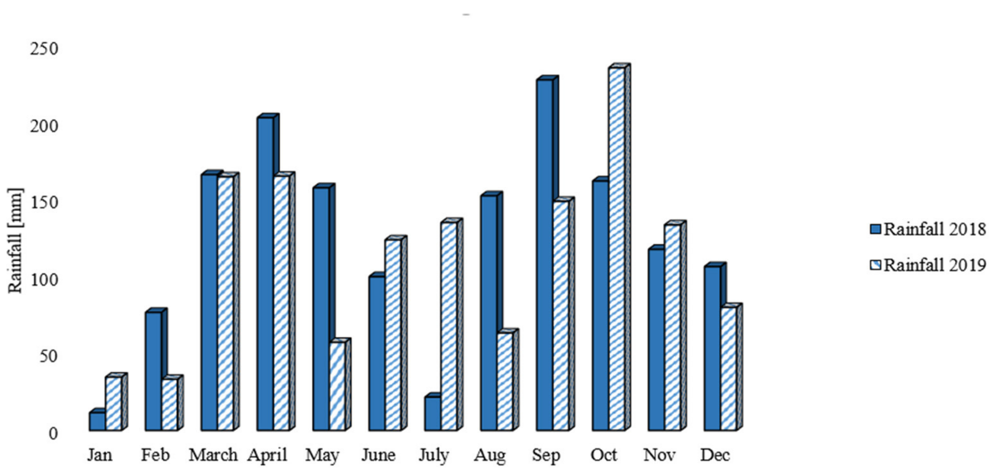

FIGURE 2
Rainfall distribution of Kamwenge district for the period of two years in 2018 and 2019. Source Ekyaligonza et al. (2022).

in Uganda. SECOW 5T cowpea variety was planted at a rate of 25 kg/ha during SR2018. This variety was selected due to its ability to survive under the dry climatic conditions of the study area; (iii) The legume *M. pruriens* var. *utilis* was selected because it grows very fast providing good soil cover, fixes a high share of nitrogen, and is adapted to dry seasons (Chakoma et al., 2016). *M. Pruriens* seed was purchased from a farmer group in Kasese district in the Rwenzori region and it was

TABLE 1 Description of treatments in the four crop-growing seasons of 2018 and 2019.

Treatments	SR2018	LR2018	SR2019	LR2019
T1	M	M + DAP + MR	M + MR	M + DAP + MR
T2	Cp	M + CpR	B + MR	M + BR
T3	Cp + FYM	M/Mpr + CpR	B + FYM + MR	M/Mpr + BR
T4	Cp +Fa	M/Mpr + Fa +CpR	B + Fa + MR	M/Mpr +Fa + BR
T5	Cp +Fa + FYM	M /Mpr + Fa +CpR	B + Fa + FYM + MR	M/Mpr +Fa + BR

Seasons: SR, short rainy season; LR, long rainy season; Treatments: T1, the inorganic fertilizer application strategy that serves as a control while T2-T5 are the organic matter management strategies; Crops: B, beans (*Phaseolus vulgaris*); BR, bean residues (residues are dry stalk and leaves incorporated into the field after harvesting the grains); Cp, cowpea (*Vigna unguiculata*); CpR, cowpea residues; Fa, *Faidherbia albida* alleys; M, maize (*Zea mays*); MR, maize residues; Mpr, *Mucuna pruriens*: Nutrient sources: DAP, diammonium phosphate (18-46-0): 50 kg/ha (N: 9 kg/ha; P_2O_5: 10.05 kg/ha); FYM, farmyard manure: 2.5 tons/ha (N: 13 kg/ha; P: 6 kg/ha; K: 18 kg/ha) as fresh matter; Symbols: + = addition of; / = intercrop.

intercropped with the 30-day-old maize at a rate of 20 kg/ha; (iv) The legume tree *F. albida* was selected because it fixes nitrogen and has reversal phenology, shedding off the leaves during the rainy season and developing leaves during the dry season. This attribute enables the trees to grow well with minimum water supply and competition with other crops (Roupsard et al., 1999). *F. albida* of Moroto provenance, which was the only seed provenance available at the Uganda National Tree seed center, was planted at a rate of 1000 seedlings/ha (one tree/10 m^2); (v). The grain legume beans (*Phaseolus vulgaris*) were included in the rotation system in SR2019 following the farmers' request to replace the cowpeas which exhibited low yields during SR2018. Beans are rich in proteins and therefore part of human diets both in urban and rural areas (Aseete et al., 2018). *Nabe 4* bean variety was selected because it matures early after 80-85 days and has high resistance against anthracnose and the bean common mosaic virus, which are the most prevalent diseases in the Rwenzori region (Kankwatsa, 2018). *Nabe 4* was sown in SR2019 at a rate of 20 kg/ha. Harvesting was done for mature crops in such a way that only maize ears or bean/cowpea pods were picked and crop residues (leaves and stalks) left in the field for further organic matter improvement. These crop residues and *M. pruriens* were chopped with a machete into smaller pieces of about 3 cm in length. The chopped material together with *F. albida* leaves were then incorporated within 0-15 cm soil depth using a hand hoe during the land tilling process. A combination of crop residues, *M. pruriens* and *F. albida* leaves is later referred to as plant residues in the subsequent sections. As indicated in Ekyaligonza et al. (2022), the quantity of plant residues that were incorporated into the soil in T1 was 18, 11, 11 and 15 tons/ha during SR2018, LR2018, SR2019, and LR2019 respectively, while those incorporated into the OMM treatments was 2.9–3.6, 24–137, 61–180, and 15–145 tons/ha during SR2018, LR2018, SR2019 and LR2019 respectively depending on the treatment. The total nutrients in these plant residues is described in Table 2. Land tilling, FYM application, sowing, two times weeding by hand pulling (the uprooted weeds were distributed in the field), and harvesting were done by the farmers under the guidance of the researchers.

When the crops were mature and ready for harvesting, dry matter (DM) yield was determined. Sample collection was done in such a way that 10 plants from each crop type were randomly selected per plot. The plants within the first two rows from the plot boundary were excluded from the sample to minimize the boundary effect. The grains and crop residues were oven-dried separately at 70°C until a constant weight was obtained. For each plot, the average DM grain yield and DM residue yield were weighed and measured as kg/ha and then converted to ton/ha. A high DM grain yield is expected to improve food and income security, while a high DM residue yield shows the potential of the cropping system to recycle biomass, improve soil organic matter and recycle nutrients.

Soil sampling and testing

Soil was sampled and tested before and after experimentation to find out the contribution of the different cropping systems (treatments) on soil fertility improvement. Initial soil sampling was conducted in January 2018 before the fields were subjected to experimental conditions to understand the level of nutrients in the soil. Final soil sampling was conducted in January 2020 to determine the contribution of each treatment to the improvement of pH, OM, WHC, N, P, and K levels in the soil. N, P, and K are macronutrients which are essential for crop growth enhancement (Lhamo and Luan, 2021), while pH, WHC and OM influence availability of nutrients to crops (Neina, 2019). In January 2018, a composite soil sample from five sub-samples was collected from each of the 10 study farms/blocks. These farms were relatively uniform in terms of terrain and vegetation. The soil sub-samples were randomly collected at 0-15 cm soil depth with an aid of a soil Auger. In January 2020 after the four-season experiment, soil sampling was repeated and a composite sample was collected from each of the 50 experimental plots.

The soil samples were tested for pH, OM, WHC, and the plant-available forms of N, P, and K. These tests can help to explain the impact of our experiments on land productivity. Soil pH was determined through an electrometric method using a pH meter (Eutech pH 700 meter). In the procedure for pH

TABLE 2 Nutrient content of plant residues recycled into the soil in the four crop-growing seasons of 2018 and 2019.

Nutrient	Total maximum nutrient content in plant residues obtained per season							
Seasons	SR2018		LR2018		SR2019		LR2019	
Treatments (T)	T1	T2-T5	T1	T2-T5	T1	T2-T5	T1	T2-T5
Nitrogen kg/ha	236	65	121	4550	162	6620	243	6620
Phosphorus kg/ha	50	286	20	384	32	411	23	411
Potassium kg/ha	398	98	199	2546	284	4141	119	3333

Source: Ekyaligonza et al. (2022).

determination, fifty (50) ml of distilled water was added to a beaker containing 20 g of air-dried soil of 2 mm particle size. The content of the beaker was stirred for 5 min. The grass electrode was then calibrated using a standard buffer of pH = 7 and pH = 4. The electrodes were then dipped into a beaker containing the soil-water suspension with constant stirring. The pH meter was then switched to pH reading and the pH value was then taken after 30 s. Organic matter was determined through the ignition of the samples at high temperatures (up to 550 °C) (Pawar et al., 2009). In the procedure for OM determination, 20 g of soil was dried at 104 °C for 24 h. It was placed on an aluminum foil and then put in an oven to dry at 550 °C for 8 h. The soil was then left to cool and then weighed. The weight difference between soils weighted before and after being subjected to very hot conditions is the OM of the soil. For WHC, 20 g of air-dried soil of 2 mm particle size was placed on a filter paper that was fixed onto the internal floor of a perforated dish. The filter paper prevents soil particles from escaping through the dish perforations. The perforated dish with its content was then placed on a trough containing water and allowed to stand for 6 h so that the soil can get saturated with water. Water holding capacity was determined by calculating the difference between the weight of air-dried soil and that of the soil saturated with water (Pawar et al., 2009). The soil N in plant-available form was determined through the hot hydrogen peroxide/potassium chloride (H_2O_2/KCl) extraction method following Sahrawat (1982) and Tie et al. (2013) where the soil was air-dried and sieved through a 2 mm sieve. Fifty (50) ml of 25% H_2O_2 was added to a 300 ml conical flask containing 5 g of sieved soil. The conical flask with its content was then placed into a ventilated oven and heated for 6 h at a temperature of 60°C. The suspension was cooled, 1 M KCl was added and the mixture rotated for 30 min. Ammonium Nitrogen (NH_4+-N) from the filtrate was determined through distillation. The plant available form of phosphorus was determined through Bray 1 extraction method in the procedure by Kovar and Pierzynski (2009) where 20 ml of Bray1 extraction solution [0.025 M hydrochloric acid (HCl) in 0.03 M ammonium fluoride (NH_4F)] was added to 2 g of soil in a 50 ml conical flask. The flask with its contents was shaken at 200 revolutions per minute at room temperature. The plant-available P was measured from the filtrate by use of a spectrophotometer (VWR- UV- 6300PC) at a wavelength of 880 nm (Kovar and Pierzynski, 2009). Potassium (K) in plant-available form was determined following a flame photometry procedure with ammonium acetate (NH_4OAc) extractant (Okalebo et al., 2002; Pawar et al., 2009) where 100 ml of NH_4OAc was added to a conical flask containing 5 g of air-dry soil sample. The flask and its content were shaken at 200 oscillations per min for 30 min and the solution was left to stand for 30 min. The supernatant was filtrated through the Whatman No. 42 filter paper and the extracted solution was diluted 10 times. Five (5) ml of the solution was pipetted into a 50 ml volumetric flask and 1 ml of lanthanum chloride solution was added. The contents were then diluted with NH_4OAc extraction solution to the mark. Potassium (K) content was determined by spraying the soil extract, lanthanum chloride, and ammonium acetate solution onto the flame of the flame photometer (PFP7 model).

Farmyard manure was analyzed for N, P, and K using Kjeldahl, Bray-1 and flame photometry methods respectively. For N, analysis followed the procedure by Hendershot et al. (1993) where 3 ml of deionized H_2O was added to a dry digestion tube containing 2 g of ground manure. Three and a half (3.5) g of K_2SO_4: $CuSO_4$ was mixed with the contents of the digestion tube and one selenized and one non-selenized Hengar granule were added. Ten (10) ml of concentrated sulphuric acid (H_2SO_4) was added and the content of the digestion tube was digested for 1.5 h at 220 °C. Air condensers were put onto the digestion tubes in the block and the temperature raised further to 360° C for 3.5 h. The samples were then cooled overnight in the block. The air condenser was then removed. Slowly and with swirling, 25 ml of deionized water was added to each cooled digestion tube. The content in the digestion tube was then transferred to a 0.5 l round bottom distillation flask and connected it to the steam distillation apparatus. One hundred (100) ml of the graduated beaker with 5 ml of 2% boric acid (H_3BO_3) was placed under the condenser. Very slowly, 30 ml of excess of 10 M sodium hydroxide (NaOH) was added through the distillation head. Forty (40) ml of distillate was collected. The distillate was titrated with 0.01 M H_2SO_4. The color change at the endpoint is from green to pink. Nitrogen was calculated from the molarity of H_2SO_4, the volume of H_2SO_4 used during titration of the sample, the volume of standard H_2SO_4 used during titration of the blank, and the mass of the oven-dried soil sample. The procedure for testing P and K was the same as that of soil.

Economic analysis

Grain revenue and gross margin calculations were conducted for each season and the total for the entire four-season rotation to establish the economic impact of the OMM strategies. The grain revenues were calculated from the yield and selling price of the grains (Equation 1). The prices used in calculating revenues were the farm gate prices of the grains in the study area in 2018 (Table 3). These prices were determined by middlemen as they are the main actors who buy produce directly from the farmers. Gross margins were calculated from the total variable costs and revenues, following other studies (Beuchelt and Zeller, 2011; Uddin et al., 2016) (Equations 1 and 2):

$$\text{Grain revenue [US\$/ha]} = \text{Yield [kg/ha] x Price [US\$/kg]} \quad (1)$$

$$\text{Gross margins [US\$/ha]} = \text{Grain revenues [US\$/ha]} - \text{Total variable costs [US\$/ha]} \quad (2)$$

The total variable costs included all the input costs, monetarized labor costs, and the total annualized costs of establishing *F. albida* alleys during the first year. Opportunity costs for the land (lease or rent), administration costs, and other fixed costs were however excluded from cost calculations, as they were fixed and therefore common factors for all treatments. The input costs were the actual costs incurred in buying inputs (Table 3). These were the costs incurred in buying maize and legume seeds, as well as fertilizers. Family labor that was used to conduct all the agronomic practices such as land preparation, manure collection and application, sowing of maize and legume seeds, and harvesting was also determined. Labor was considered a key factor hindering the establishment of OMM strategies as different treatments have different labor requirements. The labor costs were valued in terms of money as farming was the only income-generating activity for all the farming families that participated in the study. These labor costs were estimated by the farmers based on the work per completed task, which is one of the main ways of determining labor within the study area (Table 3). These labor costs were based on what hired labor would be paid for similar tasks. For the annualized costs, all the costs associated with *F. albida* tree alleys during the first year (two seasons) such as purchasing the seedlings, pitting, planting the trees as well as providing extra care not to damage the trees during land preparation and weeding of fields were considered. These costs were annualized for 20 years. A lending interest rate of 20 % per year was used, as indicated by UBOS (2019) and the World Bank database of 2018. Since there are

TABLE 3 Prices of inputs and outputs considered in the study in 2018.

Item	Unit price [$]
Input	
F. albida[seedlings]	0.09
M. pruriens[kg]	1.43
Cowpea [kg]	1.14
Beans [kg]	1.14
Maize [kg]	1.14
DAP [kg]	1.14
Labor [work per unit area]	
Land preparation [per ha]	128.57
DAP application [per ha]	14.29
1st weeding [per ha]	107.14
2nd weeding [per ha]	71.43
Harvesting [per ha]	35.71
Tending of *M. pruriens*[per ha]	14.29
Tending of *F. albida* seedlings [per ha]	14.29
Manure collection and application [per ha]	57.14
Output	
Maize grain [kg]	0.17
Cowpea grain [kg]	0.57
Bean grain [kg]	0.86
Crop residue [kg]	0.01

Exchange rate: 3500 UGX = 1$.

two crop-growing seasons per year, the annualized costs were calculated for 40 seasons (20 years), using an interest rate of 10 % per season. Annualizing costs of establishing the trees, assuming a useful life of 20 years, allows comparison of establishment costs of alley cropping systems with cropping systems that solely involve annual crops. Furthermore, it also enables farmers to know how much they need to pay back per season in case they received the total establishment costs as a loan. The annualized capital costs per season for the establishment of an alley cropping system were calculated following equation 3.

$$C = \frac{r(EC)}{1-(1+r)^{-n}} \quad (3)$$

Where,

C = Annualized capital costs per season
EC = Establishment costs
r = interest rate per season (10 %)
n = number of periods (40 seasons)

Since price fluctuation is one of the challenges that affect Uganda's agricultural production (Bamwesigye et al., 2020), a sensitivity analysis was conducted to determine the impact of price fluctuation on gross margins. This was conducted for each of the five treatments per season. For each of the three studied food crops (cowpea, beans, and maize), price scenarios were set and these included the highest, lowest, and the 2018 food prices since the harvests from our field experiment were sold starting with the year 2018. The highest, the lowest, and the 2018 prices of maize and beans were the farm gate prices. For cowpeas, the highest and the minimum prices were obtained from Ddungu et al. (2015) as the crop was traditionally not grown on a large scale in the study area. For maize, the lowest price was 0.14 US$ in 2012 (83% of the 2018 maize price) and the highest maize price was 0.29 US$ in 2015 (167% of the 2018 maize price). The lowest bean price was 0.19 US$ in 2014 (22% of the 2018 price). On the other hand, the highest bean price was the same as that of 2018. For the cowpeas, the lowest price was in 2018 while the highest was 0.63 US$ in 2009-2011 (110% of the 2018 cowpea price).

Statistical analysis

A linear mixed model (LMM) was used to analyze data as it was continuous, having "treatment" as a fixed factor and "block (farm)" as a random factor. Moreover, LMM has been documented as a suitable analysis procedure for continuous data with both the fixed factor and the random factor effects (Molenberghs and Verbeke, 2001). This data was analyzed in IBM SPSS Statistics (version 26) software using the SPSS mixed command. The dependent variables were the soil physical-chemical properties, grain yield, residue yield, grain revenue and gross margins, while the independent variable was the treatments. Data for each season was analyzed separately as the cropping systems involved rotation of different crops. The results in the table "Type III Tests of Fixed Effects" enabled us to understand whether there were significant differences in soil physical-chemical properties, grain yield, residue yield, grain revenue and gross margins among treatments while the "estimates of Fixed Effects" table enabled us to come up with pairwise comparisons of the grain yield, residue yield, grain revenue and gross margins among the treatments.

Data for the variable costs were however analyzed using an independent samples nonparametric test, as the outputs with LMM analysis could not be obtained. In addition, the data did not conform to the normality and homogeneity of variance conditions even after being subjected to transformation processes such as logarithm, natural logarithm, and Cosine.

Descriptive analysis was conducted to compare yields, costs, revenues, and gross margins among treatments and was used as a supplement to LMM and the independent samples' non-parametric tests.

Results

We compared the soil parameters in soils collected at the end of the experiment to determine the effect of the different cropping systems on soil nutrient content. In addition, we compared the parameters between the initial and final soil samples to determine any possible residual effects created by the different treatments. The yields, costs, revenues, and gross margins were compared between treatments of the same season. However, yield comparisons between seasons for the different treatments were only possible between LR2018 and LR2019 since they involved the same crops. In addition, the accumulated revenues and gross margins for each treatment across the four seasons were calculated to identify the most profitable cropping system.

TABLE 4 Baseline soil physical-chemical characteristics of the study area in January 2018.

Soil parameter	Value
pH	5.8
Organic matter [%]	2.5
Water holding capacity [%]	62
Available nitrogen content (hot H_2O_2/KCl extraction) [kg/ha]	256
Available phosphorus content (Bray 1) [kg/ha]	21
Available potassium content (NH_4OAc extractant) [kg/ha]	199

Impact of OMM strategies on soil physical-chemical properties

The soil pH was moderately acidic (pH ranges between 5.3 and 6.0) both before and after experimentation (Pawar et al., 2009) (Tables 4, 5). In addition, there were no significant differences in soil pH among all the five treatments after the experiment ($P > 0.05$) (Table 5). Like pH, the WHC was not significantly different among all the treatments after the study period ($P > 0.05$), but the amounts were higher after than before the soil was subjected to the different treatments (Tables 4, 5). The OM content of soil tested before the experiment was high, while that of soils tested after the experiment was very high (Tables 4, 5) (Pawar et al., 2009). However, the OM content of the soil collected after the experiment was not significantly different among all treatments ($P > 0.05$) (Table 5). The plant-available N content can be described as low (140–280 kg/ha) in soils tested before the experiment but high (562–700 kg/ha) in soils tested after the experiment (Pawar et al., 2009) (Tables 4, 5). In addition, plant-available nitrogen in soil collected after the experiment was not significantly different among all the five treatments ($P > 0.05$). For the plant-available P, the content was within the medium range (13–22 kg/ha) before and after subjecting the fields to the experimental conditions (Pawar et al., 2009) (Tables 4, 5). The P content in soils collected after the experiment was however not significantly different among all the treatments ($P > 0.05$) (Table 5). The plant-available K content was moderate (181–240 kg/ha) before the study and

TABLE 5 Comparison of soil physical-chemical characteristics between treatments after the experiments in January 2020.

Characteristics	T1	T2	T3	T4	T5	p-value
pH	5.5 (0.1)	5.5 (0.1)	5.5 (0.1)	5.5 (0.1)	5.5 (0.1)	ns
OM [%]	3.1 (0.2)	3.2 (0.2)	3.1 (0.2)	3.1 (0.2)	3.1 (0.2)	ns
Water holding capacity [%]	74.3 (0.2)	74.1 (0.2)	74.1 (0.2)	74.0 (0.2)	74.2 (0.2)	ns
N (hot H_2O_2/KCl extraction) [kg/ha]	537 (24.6)	506 (24.6)	519 (24.6)	506 (24.6)	489 (24.6)	ns
Bray 1- P [kg/ha]	20 (1.0)	22 (1.0)	22 (1.0)	21 (1.0)	20 (1.0)	ns
K (NH_4OAc extractant) [kg/ha]	302 (4.6)	293 (4.6)	293 (4.6)	290 (4.6)	298 (4.6)	ns

Ns, not significant; OM, organic matter; N, nitrogen; P, phosphorus; K, potassium. Values in parentheses represent the standard error of the mean.

TABLE 6 Comparison of grain and residue yields between treatments over 4 crop-growing seasons during 2018 and 2019.

Treatments	SR2018	LR2018	SR2019	LR2019
Grain yields [ton/ha]				
T1	5.5 (0.3)^{b}	4.4 (0.5)^{a}	4.4 (0.4)^{b}	5.8 (0.7)^{b}
T2	1.0 (0.3)^{a}	4.0 (0.5)^{a}	3.2 (0.4)^{a}	5.6 (0.7)^{b}
T3	0.4 (0.3)^{a}	3.5 (0.5)^{a}	2.7 (0.4)^{a}	4.8 (0.7)^{a}
T4	0.6 (0.3)^{a}	3.3 (0.5)^{a}	2.4 (0.4)^{a}	6.1 (0.7)^{b}
T5	0.7 (0.3)^{a}	4.0 (0.5)^{a}	3.0 (0.4)^{a}	7.0 (0.7)^{b}
Plant residue yields [ton/ha]				
T1	17.9 (0.7)^{b}	10.8 (0.9)^{a}	10.8 (0.8)^{b}	14.5 (1.4)^{a}
T2	2.9 (0.7)^{a}	9.8 (0.9)^{a}	7.7 (0.8)^{a}	15.4 (1.4)^{a}
T3	3.9 (0.7)^{a}	8.1 (0.9)^{a}	6.1 (0.8)^{a}	15.0 (1.4)^{a}
T4	2.9 (0.7)^{a}	8.3 (0.9)^{a}	6.1 (0.8)^{a}	15.1 (1.4)^{a}
T5	3.6 (0.7)^{a}	9.9 (0.9)^{a}	7.6 (0.8)^{a}	15.8 (1.4)^{a}

For each variable per column, values followed by different small letters $^{(a,b)}$ are significantly different at $P < 0.05$. Values in parentheses represent the standard error of the mean.

moderately high (241–300 kg/ha) after the study (Pawar et al., 2009) (Tables 4, 5). From the soil samples collected after the experimental period, there were no significant differences in plant-available K content observed among all the treatments ($P > 0.05$) (Table 5).

Impact of OMM strategies on dry matter yield of crops

A season-per-season yield comparison for different treatments showed that DM grain and residue yield were significantly higher under T1 than in OMM treatments (T2-T5) during the SR ($P > 0.05$) (Table 6). The DM grain and residue yields in T1 were however not significantly different from those in the OMM treatments during the LR except for T3 were grain yields were lowest in comparison to other treatments ($P > 0.05$) (Table 6). Considering the OMM treatments (T2-T5) in SR alone, there were no significant differences in DM grain yield and DM residue yield observed ($P > 0.05$) (Table 6). Since the treatments in LR2018 and LR2019 were similar, DM grain and DM residue yields were compared between the two seasons. The DM grain and DM residue yield however increased from LR2018 to LR2019. For instance, treatments T4 and T5 showed the highest grain yield increase of 46.3 and 42.6%, respectively from LR2018 to LR2019. T1 had the lowest grain yield increase of 24.2 %, whereas, in T2 and T3, the yield increase amounted to 29.0 and 25.9 %, respectively from LR2018 to LR2019 (Table 6). The crop residue yield increased by 25.2, 36.4, 36.9, 45.0, and 46.1% for T1, T2, T5, T4, and T3, respectively from LR2018 to LR2019 (Table 6).

Costs of establishment and maintenance of OMM strategies

Generally, the accumulated total variable costs for the entire four-season rotation system, which included an additional annualized capital cost of 25 US$ to T4 and T5 for the establishment and maintenance of *F. albida* alleys were significantly lower in T2 than in other treatments (T1 and T3-T5) ($P < 0.05$). The total variable costs for the entire four-season rotation were however not significantly different between T1, T3 andT4 ($P > 0.05$) (Table 7). In a season-per-season cost comparison, the total variable costs were significantly higher under T3 and T5 than in other treatments during SR ($P < 0.05$). For the LR, the total variable costs were on the other hand significantly higher under T1 than in treatments with OMM strategies during LR2018 but these costs were not significantly different between T1 and T3-T5 during LR2019 ($P < 0.05$) (Table 7).

Revenues and gross margins generated through establishment and maintenance of OMM strategies

The total grain revenues for the entire four-season rotation system were not significantly different among T1, T2 and T5. It was significantly higher under T1, T2 and T5 than in T3 and T4.

TABLE 7 Comparison of total variable costs incurred during implementation of treatments in the four crop-growing seasons during 2018 and 2019.

Treatments	SR2018	LR2018	SR2019	LR2019	Total
Average variable costs [US$/ha]					
T1	385.4 [a]	456.8 [c]	366.1 [a]	427.5 [b]	1635.7 [b]
T2	371.4 [a]	371.1 [a]	352.9 [a]	344.0 [a]	1439.4 [a]
T3	428.6 [b]	413.9 [b]	407.0 [b]	385.8 [b]	1635.2 [b]
T4	396.3 [a]	428.2 [b]	377.7 [a]	423.7 [b]	1626.0 [b]
T5	453.4 [b]	428.2 [b]	431.8 [b]	423.7 [b]	1737.2 [c]

For each variable per column, values followed by different small letters [(a,b,c)] are significantly different at $P < 0.05$. 25 US$ were added to T4 and T5 per season as an annualized capital cost for integrating *F. albida* alleys.

TABLE 8 Comparison of grain revenues and gross margins between treatments over 4 crop-growing seasons during 2018 and 2019.

Treatments	SR2018	LR2018	SR2019	LR2019	Total
Grain revenues [US$/ha]					
T1	933.7 (133.2) [b]	756.0 (80.0) [a]	756.0 (168.9) [a]	997.0 (114.3) [b]	3442.7 (258.8) [b]
T2	575.8 (133.2) [a]	685.3 (80.0) [a]	1819.3 (168.9) [b]	965.5 (114.3) [b]	4045.9 (258.8) [b]
T3	252.2 (133.2) [a]	605.2 (80.0) [a]	1514.3 (168.9) [b]	816.3 (114.3) [a]	3188.0 (258.8) [a]
T4	319.2 (133.2) [a]	559.3 (80.0) [a]	1386.9 (168.9) [b]	1041.9 (114.3) [b]	3307.2 (258.8) [a]
T5	373.7 (133.2) [a]	692.3 (80.0) [a]	1702.7 (168.9) [b]	1206.9 (114.3) [b]	3975.5 (258.8) [b]
Gross margins [US$/ha]					
T1	548.3 (133.2) [b]	299.2 (80.0) [a]	390.0 (168.9) [a]	569.5 (114.3) [b]	1807.0 (258.8) [b]
T2	204.4 (133.2) [a]	314.3 (80.0) [a]	1466.4 (168.9) [b]	621.5 (114.3) [b]	2606.5 (258.8) [b]
T3	−176.4 (133.2) [a]	191.3 (80.0) [a]	1107.4 (168.9) [b]	430.6 (114.3)[a]	1552.8 (258.8) [a]
T4	−52.3 (133.2) [a]	131.1 (80.0) [a]	1034. 0 (168.9) [b]	643.0 (114.3) [b]	1755.8 (258.8) [b]
T5	−54.9 (133.2) [a]	264.0 (80.0) [a]	1295.7 (168.9) [b]	808.0 (114.3) [b]	2312.9 (258.8) [b]

For each variable per column, values followed by different small letters [(a,b)] are significantly different at $P < 0.05$. Values in the parentheses represent the standard error of the mean.

From the season-per-season grain revenue comparison, it can be seen that the grain revenue in SR2018 was significantly higher under T1 than in treatments T2-T5 with the OMM strategies (Table 8). For SR2019, grain revenue was significantly higher in T2-T5 than in T1 ($P < 0.05$), and no significant differences in grain revenues were observed among treatments T2- T5 ($P > 0.05$). For the LR2018 and LR2019, no significant differences in grain revenues were observed among all the treatments (T1-T5) except T3, which yielded lower revenues than in other treatments during LR2019 (Table 8).

Gross margins followed a similar trend as the grain revenues except for the entire rotation where T3 resulted into the lowest gross margins in comparison to other treatments ($P < 0.05$). The gross margins were reduced by 28.9% for T1 and increased by 86.0, 115.9, 105.0, and 104.0% for T2, T3, T4, and T5, respectively from SR2018 to SR2019. For the long rains, the gross margins increased for all treatments by 48.0, 49.0, 56.0, 79.0, and 67.0%, and for T1, T2, T3, T4, and T5, respectively, from LR2018 to LR2019 (Table 8).

The results of the price sensitivity analysis indicate that the total gross margins under T1, T2, T3, T4, and T5 that would be obtained from the lowest prices of the crops grown in the entire rotation system would be 34, 60, 85, 72, and 66% lower than the gross margins obtained from the 2018 farm gate prices respectively. The gross margins that were calculated from the highest prices under T1, T2, T3, T4, and T5 would be 132, 45, 63, 62, and 56% higher than the ones obtained from the 2018 farm gate prices respectively (Figure 3). For the season-per-season comparison, the lowest maize price would result in 29% lower gross margins whereas the highest maize price would result in 120% higher gross margins than those obtained from the 2018 price during SR2018. For cowpeas, the price in 2018 was the lowest but the highest price would result in a 29, 15, 15, and 24% increase in gross margins for T2, T3, T4, and T5 respectively. During LR2018, the lowest maize price would result in 37, 40, 58, 86, and 52% lower gross margins for T1, T2, T3, T4, and T5 respectively than those obtained with the 2018 farm gate price. The highest maize price would result in 180, 151, 219, 287, and 177% higher gross margins for T1, T2, T3, T4, and T5 respectively than those obtained from the 2018 farm gate price. For SR2019, the lowest maize price would result in a 37% reduction in gross margins while the highest maize price would result in a 133% increase in gross margins. For beans, the lowest price would result in 84, 93, 91, and 89% lower gross margins than those obtained from the 2018 farm gate price for T2, T3, T4, and T5 respectively. The 2018 bean price was the highest

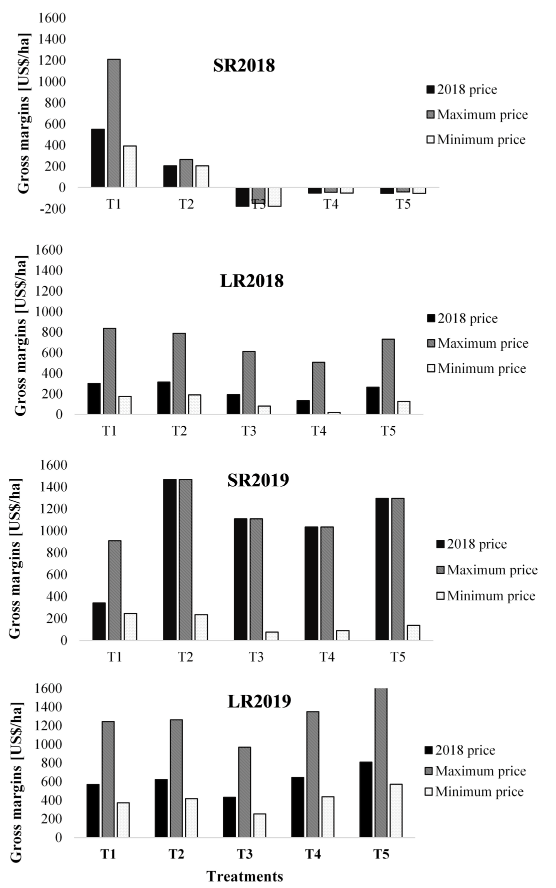

FIGURE 3
Comparison of gross margins (US$/ha) with different price scenarios among treatments over 4 crop-growing seasons during 2018 and 2019.

farm gate price from 2010 to 2018. In LR2019, the lowest maize price would result in 35, 33, 41, 32, and 29% lower gross margins while the maximum maize price would result in 118, 103, 125, 110, and 101% higher gross margins than those obtained from the 2018 farm gate price for T1, T2, T3, T4, and T5 respectively (Figure 3).

Discussion

Impact of OMM strategies on soil physical-chemical properties

The higher plant-available form of N in soils sampled after the experiment than those sampled before could be attributed to the legume-maize rotation practice for treatments T1-T4 with OMM practices and the DAP together with crop residue application for T5. Moreover, there is evidence that the inclusion of legumes into a cropping system can improve soil N and other nutrients that are crucial for crop growth (Houngnandan et al., 2000; Imoro et al., 2013; Nassary et al., 2020). The nutrients accumulated by such systems could have improved crop growth with higher grain and crop residue yields. The incorporation of crop residues into the soil could have further increased the OM and soil nutrients. These results are in agreement with a study by Bu et al. (2020) where crop residue incorporation increased soil organic carbon and total N concentrations by 18.81 and 22.73%, respectively in a 12-year experiment that was established in 2007. Water holding capacity was higher after the experiment (74.0–74.3 %) than before (62%). This could be explained by the organic matter formed after the decomposition of the crop residues incorporated in all the treatments. The pH levels were however within the same range before and after the experiment, possibly, because both soil sample sets were collected in the same month although in different years (January 2018 and 2020). The plant-available P content from DAP in T1 and the different combinations of OMM strategies in the other treatments did not substantially change, compared to the situation before the trials. The reason might be the low nutrient contribution by the applied 50 kg/ha DAP for T1 and the organic materials such as crop residues incorporated in T2-T5 or export of nutrients *via* crop harvest for all treatments.

The similar effect in pH, WHC, and the plant-available forms of N, P, and K after the experiment could be explained by the nutrient uptake by the crops during the crop growing season as the soil was sampled 1 week after harvesting the grain.

The soil after our experiments had higher N and K levels (489–537 and 290–302 kg/ha respectively) compared with the recommended nutrients (180, 74 and 157 kg/ha of N, P and K respectively) that are required for proper maize growth (MAAIF, 2019). However, the P levels (20–22 kg/ha) were below the recommended levels. If phosphorus levels were increased, the yields would probably increase further. Since this study only focused on macronutrients, future studies should also test the impact of OMM strategies on soil micronutrients.

Impact of OMM strategies on dry matter yield of crops

Organic matter management is an important strategy for improving soil fertility and DM crop yield (Lupwayi et al., 2011; Akmal et al., 2015; Beuschel et al., 2019; Bu et al., 2020). The significantly higher DM grain and residue yield in T1 than in the OMM treatments (T2-T5) during SR could be explained by the different crops integrated into the different treatments as T1 involved maize while T2-T5 had cowpeas during SR2018 and beans in SR2019. In the LR, the observed DM maize grain yields for all the treatments were 1.8–5.5 tons/ha higher than the 1.5 tons/ha average yield reported on some Ugandan farms that neither employ hired labor nor apply organic manure and mineral fertilizers (Simtowe et al., 2019). This could be explained by the multiple pre-crop effects on soil characteristics and nutrient supply for treatments T2-T5, and the crop residues and DAP fertilizer that were applied under T1. For instance, the higher maize yield of 4 tons/ha in T2 during LR2018 than the 1.5 tons/ha average Ugandan farmers' yield could be related to the N2 fixed and other nutrients added to the soil by cowpea biomass accumulated during SR2018. These results are in agreement with Vesterager et al. (2007) in a Tanzanian farm where maize yield doubled in a field when maize followed a cowpea pre-crop compared to a maize mono-cropping system.

A similar effect in DM grain and residue yields during LR among all the five treatments is not surprising. It could be attributed to the improved soil OM and availability of N and K that resulted from the application of the OMM strategies for T2-T5 and the inorganic fertilizer DAP and maize residues for T1. This similar effect is an indicator that the cereal-legume rotation system and crop residue incorporation for treatments with OMM strategies can result in yields that are similar to the ones in T1 with 50 kg/ha DAP fertilizer and maize-crop residue incorporation.

The higher maize grain and residue yield in LR2019 than in LR2018 could be explained by several factors. First, the better rainfall distribution in LR2019 than in LR2018 could have supported crop growth hence higher yields in LR2019. In addition, the lower maize yield in LR2018 than in LR2019 might be an effect of the leaching processes that resulted from the higher rainfall in LR2018 (plus 78.2 mm) in a period where the soil was still not fully covered by organic matter. Secondly, the higher DM yields in the LR2019 could also be attributed to the decomposition of plant residues as reported by Bu et al. (2020) in a study where soil organic carbon, organic matter, and macro aggregates increased after the decomposition of the crop residues. Moreover, the plant residues in the OMM strategies contained up to 6620, 411, and 3333 kg/ha of total N, P and K respectively while those under the fertilizer application strategy contained 243, 23 and 119 kg/ha of total N, P and K respectively (Ekyaligonza et al., 2022). For T2-T5, the higher maize yield during LR2019 than in LR2018 could have occurred as feedback on the incorporated crop residues of the bean pre-crop in SR2019 and its N2 fixation (see also Nassary et al., 2020). Thirdly, the organic matter accumulation by the OMM treatments could have improved soil nutrients and crop growth hence higher maize yields. Moreover, OMM strategies such as FYM application can improve soil nutrients that would favor crop growth (Motsi et al., 2019). In addition, FYM application improves soil organic carbon, which in turn influences the soil's physical properties responsible for improving crop growth (Xiao et al., 2022). The impact of FYM on yield was also observed in trials by Shibabaw et al. (2018) where FYM was applied in the field at a rate of 5 tons/ha, and Kumar et al. (2011), where it was applied at a rate of 12 tons/ha. Fourthly, the higher crop yield under the treatments with *F. albida* could be explained by nitrogen fixation as *F. albida* trees are known to fix about 39 kg N/ha/year (Toure et al., 1998; Umar et al., 2013), but the amount of nitrogen fixed is expected to increase as the trees grow. *F. albida* is also known for improving soil organic carbon (SOC), total N, available P, and total K (Birhane et al., 2018; Yengwe et al., 2018), but also for other nutrients accumulated in the branches. The maize yield in treatments with *F. albida* alleys was however higher than the amounts observed in Yengwe et al. (2018) where maize yield in fields with 8, 12, and 22-year F. albida trees with DM litter-fall of 0.9–3.9 ha−1 from 2014–2016 was analyzed. The yield difference between what is observed in the current study and other studies could be attributed to the additional role of other OMM strategies such as crop rotation, integration of M. pruriens, and crop residue incorporation that were applied into the field. Crop yields are expected to increase when *F. albida* alleys attain an age of about 20 years (Dilla et al., 2019). Fifth, M. pruriens which was intercropped with maize in treatments T3-T5 could have also contributed to nitrogen fixation, which in other trials in Africa is estimated to fix up to 177 kg N/ha, as well as increasing the SOC, and other minerals in plant-available forms (Houngnandan et al., 2000; Imoro et al., 2013). Under climate conditions similar to those of the study area, the decomposition of M. pruriens can be attained within 6–7 weeks (Saria et al., 2018). An increase in DM maize grain yield in LR2019 for the treatments with OMM strategies is an indicator that the strategies can improve both food and income security.

For the DM residue yield, its increase under the OMM treatments during the LR2019 shows that the applied cropping systems have the potential to increase biomass, which when incorporated into the soil can recycle the nutrients hence improving the soil organic matter. In the subsequent years, it can be expected that the OMM strategies' additional biomass, nitrogen, and higher availability of nutrients can lead to higher soil fertility with positive impacts on crop yields than what we observed in LR2018 and LR019.

Costs of establishment and maintenance of OMM strategies

The application of OMM strategies is expected to improve crop yield with lower costs incurred than the inorganic fertilizer application strategy. Our results show that T2 involved significantly lower accumulated variable costs than all the treatments during the entire four-season rotation. This could be explained by the lowest labor and seedling costs incurred during the establishment and maintenance of the cropping system in comparison to other treatments. Indeed, T2 only involved the application of simple OMM strategies; majorly maize-legume rotation and crop residue incorporation without incurring any cost of purchasing DAP, as well as preparing and applying FYM.

During SR, the total variable costs incurred were higher under T3 and T5 than all other treatments, and this could be attributed to the extra labor costs of 57.15 and 54.05 US$/ha that were incurred for each of the two treatments during SR2018 and SR2019, respectively. These extra costs resulted from dung collection from the livestock farm and the preparation and application of FYM in the field. These extra labor costs can however enable farmers to generate additional income on their farms. Conversely, the higher total variable costs under T1 than the treatments T2-T5 with OMM strategies during LR2018 could be explained by the cost incurred in purchasing DAP fertilizer and the labor costs for applying it in the field. This study shows that the costs involved in the application of OMM treatments begin to reduce by the second season when the same crop is grown.

Revenues and profits generated through establishment and maintenance of OMM strategies

During the SR2018, the higher revenues and gross margins obtained in T1 than in the treatments T2-T5 with OMM strategies could be explained by the different crops planted in the different treatments since T1 involved maize monocrop while treatments T2-T5 involved cowpeas. The maize and cowpeas differed in yield and price, hence affecting the grain revenues and gross margins. The lower revenues and gross margins under T1 than in treatments with OMM strategies in SR2019 could be explained by the lower selling price of maize (0.17 $/kg) that was planted under T1 than the beans (0.86 $/kg) planted under T2-T5.

Obtaining a similar effect in terms of grain revenues and gross margins among treatments T1, T2, T4 and T5 during the LR where maize was a common crop for all treatments could be explained by the impact of the different soil amendment strategies. Moreover, the yields obtained were not significantly different among the same treatments in the LR. From the gross margin results obtained during the LR and the total gross margins after the entire four-season rotation, this study suggests that the OMM strategies, while contributing more to soil fertility, as shown in several studies (Lupwayi et al., 2011; Akmal et al., 2015; Birhane et al., 2018; Beuschel et al., 2019; Bu et al., 2020), are as profitable as the inorganic fertilizer application strategy.

The price sensitivity analysis showed that all the crops in this study are affected by price fluctuation, which would in turn affect gross margins. Based on the range of gross margins in SR2018 and LR2018, the results indicate that T1 has a higher sensitivity to price fluctuation while T4 has the least in comparison to other treatments. This could be explained by the higher maize price fluctuation in T1 than in cowpeas that were planted in T2-T5. In SR2019, T2 showed the highest sensitivity to price fluctuation while T1 showed the least in comparison to other treatments. This could be explained by the higher bean price fluctuation compared to the maize. In the LR2019, T5 showed the highest sensitivity to price fluctuation while T3 showed the least in comparison to other treatments. The total gross margins of the entire rotation system however indicate that T1 has the highest sensitivity to price fluctuation while T3 has the least, in comparison to other treatments. Based on the gross margin trends per season and the total gross margins for the entire rotation system, it can be seen that T1 is the riskiest strategy while T3 and T4 are the least risky strategies in comparison to T2 and T5. The lower sensitivity levels of gross margins under T3 and T4 than the maize monocropping system in T1 could be explained by the wide maize price fluctuations in comparison to the diversified rotation systems in T3 and T4. This implies that T3 and T4 would have a higher adoption potential by the smallholder farmers than T1, T2, and T5.

Conclusion

During this two-year study, the OMM strategies attained similar maize crop yield as the mono-cropping system with DAP and maize residue application. Future effects of OMM strategies on soil productivity can be expected on this sandy, low-pH soil with a low buffer capacity. In addition, the revenues and gross margins from the maize yields under the treatments with OMM strategies were similar to the mono-cropping / inorganic fertilizer application approach. Moreover, the total variable costs, inclusive of monetarized family labor were higher in the treatment with inorganic fertilizer application than in the treatments with OMM strategies during LR2018 and they were not significantly different from the OMM strategies of T3-T5 during LR2019. In addition, the application of OMM strategies proved to be as profitable as the inorganic fertilizer application strategy. The continuation of OMM is expected to increase soil fertility indicators and consequently crop yield and farm economy. The price sensitivity analysis however showed that the gross margins under T3, which involved FYM application, maize-*M. pruriens* intercrop and a legume-maize rotation; and T4, which involved *F. albida* alleys, maize-*M. pruriens* intercrop and a legume-maize rotation are less sensitive to price fluctuation. Due to this advantage, T3 and T4 have a high adoption potential by smallholder farmers. Moreover, smallholder farmers can access the planting materials for T3 and T4.

The results of this study were however based on only four crop-growing seasons. Both cropping systems are at risk of soil-borne diseases and need further development. Future studies should be conducted for at least eight seasons (four years), involving at least four food crop families or different cereals to ascertain whether the OMM strategies will increase the yields and profits in subsequent crop-growing seasons, as well as analyze the effects on soil fertility indicators. Another study should consider varying FYM and nutrient levels to determine whether the results will be different from what we observed. The soil micronutrient levels should also be determined in future studies. Since phosphorus was low in all treatments before and after experimentation, future studies should also consider the inclusion of an input with liming effect for the inorganic fertilizer application treatment and the plant materials that can increase phosphorus in the OMM treatments.

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

DE conceptualized the idea, established the field trials, conducted data collection, and conducted the statistical analysis. DE and ME conducted the economic analysis. DE and TT wrote the first draft. JK, JF, and BF supervised the research. DE, TT, PD, JK, ME, JF, and BF reviewed and edited 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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Limited yield penalties in an early transition to conservation agriculture in cotton-based cropping systems of Benin

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Transitioning toward minimum or no tillage is challenging for smallholder farmers in sub-Saharan Africa (SSA), due to the possible yield penalties during the initial years of a transition. Understanding the early impacts of such transitions is crucial in a cash crop such as cotton, on which farmers rely for their income, and is necessary to inform agroecological strategies to cope with both these challenges. This study explores the combined impact of minimum or no tillage and fertilizer regimes on agronomic parameters of cotton–cereal rotations, as practiced by smallholder farmers in Benin. A multilocation experiment was set up in three different agroclimatic zones, namely, Savalou (7°55′41″, 1°58′32″), Okpara (2°48′15″, 7°72′07″), and Soaodou (10°28′33″, 1°98′33″). In each area, the experiment was laid out as a split-plot design with four replications (main plot = soil preparation; subplot = fertilizers regimes). The treatments consisted of three different forms of soil preparation, namely, tillage, strip tillage, and no tillage or direct seeding, and four fertilization regimes, namely, basal mineral fertilizers (BMF, 200 kg ha^{1} of $N_{14}P_{18}K_{18}S_{6}B_{1}$ + 50 kg ha^{1} of urea), BMF + A (200 kg ha^{1} of calcium phosphate amendment, $22P_2O_5$-43CaO–4S), BMF + C (400 kg ha^{1} of compost), and BMF + A + C. At all sites, direct seeding led to lower below-ground biomass growth and seed cotton yields compared with conventional tillage in an early transition to conservation agriculture starting from degraded soils (2% to 25%). Weak rooting under direct seeding resulted in lower cotton yields compared with that under tillage (−12%) and strip tillage (−15%). At 45 and 90 days after emergence, cotton plants were shorter under direct seeding compared with tillage (−9% and −13%, respectively) and strip tillage (−23% and −6%, respectively). Fertilizer regimes affected seed cotton yields differently across sites and treatments, with marginal responses within soil preparation methods, but they contributed to increase yield differences between conventional and no tillage. Considering the need for sustainable practices, in the context of degraded soils and poor productivity, such limited yield penalties under CA appear to be a reasonable trade-off in the first year of a transition. Alternatively, the results from the first year of this experiment, which is meant to continue for another 5 years, suggest that strip tillage could be a sensible way to initialize a transition, without initial yield penalties, toward more sustainable soil management.

KEYWORDS

yield penalties, direct seeding, strip tillage, root, biomass, conservation agriculture, cotton

Highlights

- Conventional tillage, strip tillage, and direct seeding were tested in three cotton-growing regions of benin.
- At all the sites, yields were 6–20% lower under direct seeding than those under conventional tillage.
- increasing fertilizer inputs did not contribute to overcoming such yield declines under conservation agriculture.
- Observed yield penalties were associated with lower root numbers and below-ground biomass.
- Strip tillage appears as a sensible way to initialize a transition toward more sustainable soil management.

Introduction

Soils in sub-Saharan Africa (SSA) are degraded, mainly due to the expansion and intensification of agriculture in efforts to feed its growing population (Tully et al., 2015). Soil degradation affects the livelihoods of the majority of the population that depends directly on agriculture for food and income. There is an urgency in transitioning toward more sustainable soil management practices in SSA, particularly in Benin, where soils are extremely degraded. Conservation agriculture (CA) has the potential to halt soil degradation and even restore their productivity over the long term in SSA (Thierfelder et al., 2016; Ranaivoson et al., 2017; Kassam et al., 2019; Martinsen et al., 2019). CA is based on a set of sustainable agricultural practices that fulfill the following three main principles: (1) minimal soil disturbance or no tillage/direct seeding; (2) continuous soil cover—with crops, cover crops, or a mulch of crop residues; and (3) crop rotation and the use of cover crops (FAO, 2015). There is scientific evidence that CA can enhance crop yields (Mupangwa et al., 2019), especially when all three principles are deployed together (Corbeels et al., 2020). Several studies, however, reported contradictory results on the impact of CA on soils, crop productivity, and weed infestation, and these discrepancies need to be understood (Giller et al., 2009; Ranaivoson et al., 2017; Alarcón et al., 2018; Ginakes et al., 2018; Nafi et al., 2020; Buesa et al., 2021; Singh et al., 2021).

Published research on no tillage/direct seeding shows that it can maintain, increase, or decrease yield levels over time (Giller et al., 2009; Brouder and Gomez-Macpherson, 2014). A number of studies showed that no tillage/direct seeding practices can reduce crop yield due to the potential for soil waterlogging and/or cooler soil temperatures which can inhibit the nutrient release and crop growth (Ogle et al., 2012). Minimum tillage, on the contrary, has been proposed as an alternative to no tillage and widely discussed in the literature, with divergent effects reported depending on the type of crop, the biophysical conditions, and the timescale of the practice (Githongo et al., 2021). When compared with no tillage, minimum tillage may have a minor positive or neutral impact on crop dry matter and grain yield (Conyers et al., 2019). Minimum tillage was shown not to improve soil quality parameters, yield, the productivity of wet season and winter crops and cropping systems, net yields, or water use efficiency (Singh et al., 2021).

One of the factors that deter farmers in sub-Saharan Africa from transitioning toward CA is the initial yield penalties they may experience (Tittonell et al., 2012). Most of the existing studies involving minimum tillage or no tillage/direct seeding investigated the long-term impact of those agricultural practices. Very few studies have focused on the impact of minimum tillage or no tillage/direct seeding on agronomic and environmental parameters at the early phase of the transition, and they show varying impacts (positive, neutral, or negative) (Baudron et al., 2012; Gill and Aulakh, 1990; Thierfelder and Mhlanga, 2022). For example, Mafongoya et al. (2016) reported yield penalties under direct seeding during the first 2 years, but not after subsequent years. Such short-term effects are important because they determine the attractiveness of CA to farmers and thus its potential for adoption. The variability in short-term crop responses to CA is primarily due to the interactive effects of crop needs, soil characteristics, and the climate (Giller et al., 2009). Also, several studies have shown a need to initially increase fertilizer inputs in CA systems due to a short-term decline in nitrogen availability (Sainju et al., 2006).

The objective of this study was to investigate the combined effect of soil preparation methods (tillage, strip tillage, and no tillage) and different fertilization regimes on seed cotton yields, the main cash crop in Benin, during the first year of a long-term experiment. We hypothesized that adjusted fertilization regimes, adding compost and calcium phosphate, may contribute to overcoming the initial yield penalties expected during the first steps in a transition to conservation agriculture, relying on no or minimum tillage, and starting from moderately degraded soils. A multilocation trial was established in three cotton-growing regions of Benin, which exhibit poor soils that were historically managed under conventional tillage, and is meant to be conducted over 5 years. Here, we focus on the first 2 years of the experiment (cover crop + main crop) to assess the extent of yield penalties in the early phases of the transition toward CA and hence to be able to quantitatively characterize the trade-off between short-term productivity and long-term soil fertility restoration under CA.

Materials and methods

Site description

This study was carried out during the 2021 growing season in three different agroclimatic zones of Benin, namely, Savalou, Soaodou, and Okpara (Figure 1). Savalou (7°54′24″, 1°55′31″) is part of the Sudano-Guinean climatic zone, which is characterized by a growing season with a bimodal distribution, allowing two crops per year. The precipitations were approximately 1,000–1,200 mm, spread over a vegetative growth period of 240 days, and one constant and intermediate dry season. During the growing season, the rainfall period spans from March to July and September to November. The soils at Savalou are ferruginous tropical soil (Haplic Luvisol) according to the World Reference Base classification (FAO, 2006). The soils are sandy with low clay. The soils are not particularly fertile and require the application of agroecological practices to improve soil fertility.

The experimental center of Soaodou (10°29′42″, 1°99′05″) is located at Péhunco, a city in the northwest part of the country. Soaodou is characterized by a Sudano-Sahelian climate with an average unimodal rainfall of 900–1,300 mm of water per year. The growing season ranges from May to November and the dry season ranges from December to April. The vegetative growth period is between 140 and 189 days. The soils at Soaodou are Fluvisols according to the World Reference Base classification (FAO, 2006). Soil type and physicochemical characteristics at the experimental sites are presented in Table 1.

The experimental center of Okpara (9°21′11″, 2°41′02″) is located 10 km from the city of Parakou. Okpara is characterized by a Sudanian climate with an average unimodal rainfall ranging from 900 mm to 1,200 mm and an average daily temperature of approximately 27.5°C. It is also characterized by a growing season extending from May to October and a dry season from November to April. The soils are classified as ferruginous tropical soil in the French system of classification of soils, which corresponds to Acrisols or Lixisols according to the World Reference Base classification (FAO, 2006).

Experimental design and layout

A multilocation experiment was conducted for one season under a split-plot design with four replications (main plot =

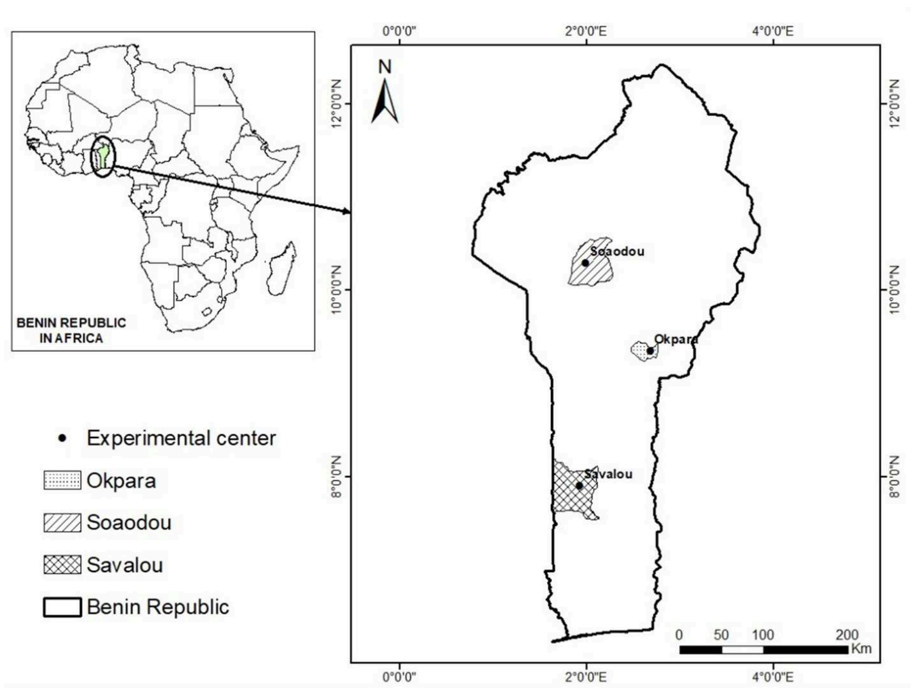

FIGURE 1
Experimental centers location at Benin Republic.

TABLE 1 Physico-chemical characteristics of the soil at experimental sites.

Site	Soil type	Physical parameters	Chemical parameters in 2019						
			C total (g kg^{-1})	N total (g kg^{-1})	P (g kg^{-1})	K (cmol$^+$ kg^{-1})	Ca (cmol$^+$ kg^{-1})	Mg (cmol$^+$ kg^{-1})	Na (cmol$^+$ kg^{-1})
Soaodou	Luvisols	High clay content	0.44	0.59	5.9	0.10	1.95	0.43	0.21
Okpara	Aerisols or Lixisols	Sandy loam	0.54	0.58	14	0.12	1.36	0.39	0.19
Savalou	Haplic Luvisol	Sandy with low clay	0.71	0.59	15.9	0.39	3.26	0.63	0.21

TABLE 2 Seed cotton yield (kg ha^{-1}; means are followed by standard deviation).

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	1290 ±66 c	1578 ± 76 b	1333 ± 48 c
Strip till	1433 ±47 a	2091 ± 53 a	1499 ± 88 a
Tillage	1399 ±35 b	1983 ± 55 a	1425 ± 43 b
Yield penalty (%) direct seeding/tillage	8 %	20%	6%
Fertilizers regimes			
BMF	1421 ± 73 a	1917 ± 71 a	1415 ± 97 a
BMF + A	1342 ± 36 b	1908 ± 98 a	1418 ± 67 a
BMF + C	1330 ± 60 b	1838 ± 98 a	1412 ± 61 a
BMF + A + C	1402 ± 65 a	1872 ± 90 a	1426 ± 67 a
Soil preparation: Fertilizers regimes			
Direct seeding: BMF	1380 ± 210 bcd	1745 ± 129 a	1231 ± 59 f
Direct seeding: BMF + A	1246 ± 56 ef	1548 ± 170 a	1343 ± 131 e
Direct seeding: BMF + C	1219 ± 109 f	1499 ± 205 a	1395 ± 94 de
Direct seeding: BMF + A + C	1314 ± 146 de	1520 ± 114 a	1365 ± 102 de
Strip till: BMF	1476 ± 109 a	2067 ± 89 a	1677 ± 241 a
Strip till: BMF + A	1454 ± 51 ab	2191 ± 151 a	1524 ± 139 b
Strip till: BMF + C	1394 ± 96 abcd	2041 ± 78 a	1262 ± 128 f
Strip till: BMF + A + C	1406 ± 134 abc	2063 ± 116 a	1486 ± 166 bc
Tillage: BMF	1406 ± 46 abc	1937 ± 133 a	1338 ± 101 e
Tillage: BMF + A	1326 ± 42 cde	1985 ± 60 a	1387 ± 81 de
Tillage: BMF + C	1376 ± 115 bcd	1975 ± 121 a	1550 ± 75 b
Tillage: BMF + A + C	1485 ± 58 a	2034 ± 140 a	1426 ± 88 cd
Soil preparation	0.00 ***	0.00 ***	0.00 ***
Fertilizers regimes	0.00 ***	0.85 ns	0.95 ns
Soil preparation: Fertilizers regimes	0.00 ***	0.80 ns	0.00 ***

**, ***significant at 5 % (0.01 < P < 0.05), and 1 % (P < 0.01), respectively; ns, not significant at P ≤ 0.05. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

soil preparation; subplot = fertilizers regimes). The basic plot size was 96 m^2. The treatments consisted of three different forms of soil preparation, namely, tillage (CT), strip tillage (ST), and no tillage or direct seeding (DS), and four fertilization regimes, namely, basal mineral fertilizers (BMF, 200 kg ha^{-1} of $N_{14}P_{18}K_{18}S_6B_1$ + 50 kg ha^{-1} of urea); BMF + A (200 kg ha^{-1} of calcium phosphate amendment, $22P_2O_5$-43CaO−4S) at the emergence, near the seeding line; BMF + C (400 kg ha^{-1} of compost) at the emergence, near the seeding line; and BMF + A + C at the emergence, near the seeding line. NPKSB and urea were applied on the plots at 15 and 40 days, respectively, after emergence. The plots were cultivated with two varieties of cotton (*Gossypium hirsutum* L.) recommended according to the agroecological zones. The varieties represent those that are disseminated in each area, OKP 768 at Savalou and Okpara and ANG 956 at Soaodou. A tiller was used to prepare the soil on tillage and strip till plots. The strip till was set up in dry conditions, in March at Savalou and at the beginning of May at Soaodou and Okpara. In the first season, *Crotalaria juncea* was sown on all the plots after the first precipitations. On the till plots, tillage was done in the second season, at a depth of 20 cm, using a moldboard plow by burying *Crotalaria* crop residues. At Savalou, Okpara, and Soaodou, the plots were prepared with glyphosate (480 g l^{-1}) 15 days before cotton seeding to control soil weeds. After the glyphosate, the roller was used to put down the biomass. Seeding was performed early (15 days before tillage plots) on the strip till and direct seeding plots after important precipitations. Seeding was performed manually at 0.80 m inter-row and 0.2 m on the row with three or four seeds per hole. The seedlings were separated 15 days after emergence by keeping one plant per pocket, which means 41,666 plants per hectare. Weed management and phytosanitary protection were carried out according to the technical recommendations for cotton production in Benin (Houndete et al., 2015).

Agronomic data collection

Roots and below-ground biomass were estimated through the number of roots and the elbow frequency. Above-ground and below-ground biomass was measured 40 days after emergence. Plant height was measured at 30, 45, and 90 days after emergence. On two lines, after three steps along the first line, the first plant was measured and marked with a wire. The 14 following plants were measured and the same sampling was performed on the second line. Seed cotton yields were estimated on the central lines. The first harvest was performed when 50% of the capsules were opened, and the second harvest was performed when all the capsules were opened.

Data analysis

The statistical analysis was performed using the R statistical software (v4.1.2; R Core Team, 2021). Prior to analysis, the data were curated and extreme outliers were removed. Descriptive statistics were obtained using the psych package. Variables that satisfied the conditions of normality and homoscedasticity were subjected to an ANOVA using the split-plot design. The Student–Newman–Keuls test was used to separate the significantly different means. A probability level at a p-value of ≤ 0.05 was used as the critical value. The analysis of area clustering was performed using the linear mixed-effect model and the generalized linear mixed model using the Template Model Builder. Tukey's test was used to compare the estimated means obtained with the function "lsmeans."

Results

Seed cotton yields

Yields in the three regions were in the order of those obtained by local farmers on average (1,200 kg ha^{-1}), significantly ($p < 0.05$) greater at Okpara (1884.31 ± 44.40 kg ha^{-1}) than at Savalou and Soaodou (1410.38 ± 36.79 and 1373.92 ± 30.03 kg ha^{-1}, respectively). On average, seed cotton yields were significantly ($p < 0.05$) lower under direct seeding than those under conventional (−6, −20, and −8%, at Savalou, Okpara, and Soaodou, respectively) or strip tillage (−9.4, −24.5, and −9.9% at Savalou, Okpara, and Soaodou, respectively; Table 2). Yields under strip tillage were higher than those under conventional tillage at Soaodou and Savalou. There were no significant ($p > 0.05$) differences across fertilizers regimes at Okpara and Savalou. At Soaodou, basal mineral fertilizers regimes and basal mineral fertilizers with compost and calcium phosphate amendments produced significantly ($p < 0.05$) higher seed cotton yields compared with the other regimes. Absolute yield differences between conventional tillage and no tillage or direct seeding varied across sites, and were much wider at Okpara and tended to increase with full fertilization regimes (Figure 2).

Above-ground biomass

The patterns of variation observed for seed cotton yields were partially also reflected in the variation of above-ground biomass growth, which was assessed 40 days after emergence (Table 3). On average, plants established through direct seeding exhibited the same levels of above-ground biomass 40 days after emergence compared with the conventional tillage at

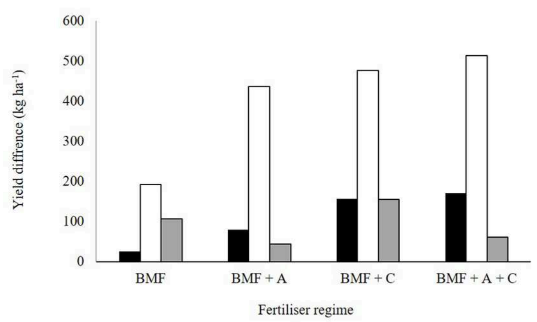

FIGURE 2
Absolute seed cotton yield differences (kg ha^{-1}) between conventional tillage and no till at Soaodou (black bars), Okpara (white bars) and Savalou (grey bars). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N).

TABLE 3 Aboveground biomass (g plant^{-1}) at 40 days after emergence (means are followed by standard error).

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	8.32 ± 0.89 a	9.15 ± 0.73 b	8.62 ± 0.31 b
Strip till	10.36 ± 1.24 a	12.46 ± 1.48 a	12.77 ± 0.53 a
Tillage	10.71 ± 1.33 a	9.99 ± 0.70 b	12.26 ± 1.55 a
Fertilizer regimes			
BMF	11.46 ± 1.61 a	11.06 ± 0.95 a	11.02 ± 0.86 a
BMF + A	9.05 ± 0.61 a	9.84 ± 1.80 a	10.72 ± 1.07 a
BMF + C	7.99 ± 1.67 a	11.27 ± 1.05 a	10.02 ± 1.21 a
BMF + A + C	10.70 ± 1.17 a	9.95 ± 1.18 a	13.10 ± 1.68 a
Soil preparation: Fertilizer regimes			
Direct seeding: BMF	8.46 ± 2.43 a	10.11 ± 2.26 a	7.96 ± 0.33 b
Direct seeding: BMF + A	8.65 ± 1.45 a	8.83 ± 1.19 a	8.06 ± 0.92 b
Direct seeding: BMF + C	8.69 ± 2.56 a	10.13 ± 1.21 a	9.27 ± 0.44 b
Direct seeding: BMF + A + C	7.50 ± 1.48 a	7.51 ± 1.15 a	9.22 ± 0.47 b
Strip till: BMF	10.95 ± 1.54 a	12.59 ± 1.98 a	12.94 ± 0.45 ab
Strip till: BMF + A	8.34 ± 0.66 a	13.56 ± 4.89 a	13.76 ± 0.55 ab
Strip till: BMF + C	13.20 ± 3.22 a	12.21 ± 3.71 a	13.41 ± 1.27 ab
Strip till: BMF + A + C	8.96 ± 3.67 a	11.50 ± 2.34 a	10.96 ± 1.28 b
Tillage: BMF	14.96 ± 3.48 a	10.49 ± 0.30 a	12.16 ± 1.16 b
Tillage: BMF + A	10.16 ± 0.99 a	7.14 ± 1.63 a	10.36 ± 2.10 b
Tillage: BMF + C	10.21 ± 3.33 a	11.47 ± 0.72 a	7.39 ± 2.51 b
Tillage: BMF + A + C	7.51 ± 0.41 a	10.85 ± 1.33 a	19.13 ± 1.96 a
Soil preparation	0.12 ns	0.03 **	0.00 ***
Fertilizers regimes	0.07 ns	0.70 ns	0.05 ns
Soil preparation: Fertilizers regimes	0.48 ns	0.63 ns	0.00 ***

*, *** significant at 5 % (0.01 < P < 0.05), and 1 % (P < 0.01), respectively; ns, not significant at P ≤ 0.05. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

Soaodou and Okpara (Table 3). However, at Savalou, above-ground biomass was significantly ($p < 0.05$) lower under direct seeding compared with conventional tillage. Similarly, above-ground biomass was greater at Okpara and Savalou compared with Soaodou ($p < 0.05$). Fertilizer regimes did not affect the above-ground biomass between the sites or treatments in our experiment.

Above-ground biomass growth was also assessed non-destructively, by measuring plant height at 30, 45, and 90 days after emergence (Figure 3). At 30 days after emergence, no significant differences in plant height were observed between the different soil preparation treatments at any of the locations ($p > 0.05$). At 45 days after emergence, only at Okpara soil preparation affected plant height, where plants under direct seeding were 34% shorter than those under conventional tillage ($p < 0.05$). No significant differences in plant height were observed across soil preparation treatments at Savalou and Soaodou. At 90 days after emergence, plants were significantly shorter under direct seeding than those under conventional or strip tillage at Okpara and Soaodou (−20 and −18%, respectively) ($p < 0.05$). Fertilizer regimes did not significantly ($p < 0.05$) affect the cotton plant height at 30, 45, or 90 days after emergence at any of the three experimental sites.

Below-ground biomass and roots

Below-ground biomass

The observed differences in yield and above-ground biomass between treatments were not consistently reflected by root biomass. At 40 days after emergence, plants established through direct seeding had less below-ground biomass than those under conventional tillage and similar average values as under minimum strip tillage (Table 4). However, these differences in means can be explained by the differences observed at Soaodou and Savalou, but not at Okpara. Similarly, root biomass was significantly ($p < 0.05$) greater at Okpara and Savalou than at Soaodou ($p < 0.05$). Fertilizer regimes did not affect the below-ground biomass at any of the experimental sites or across treatments.

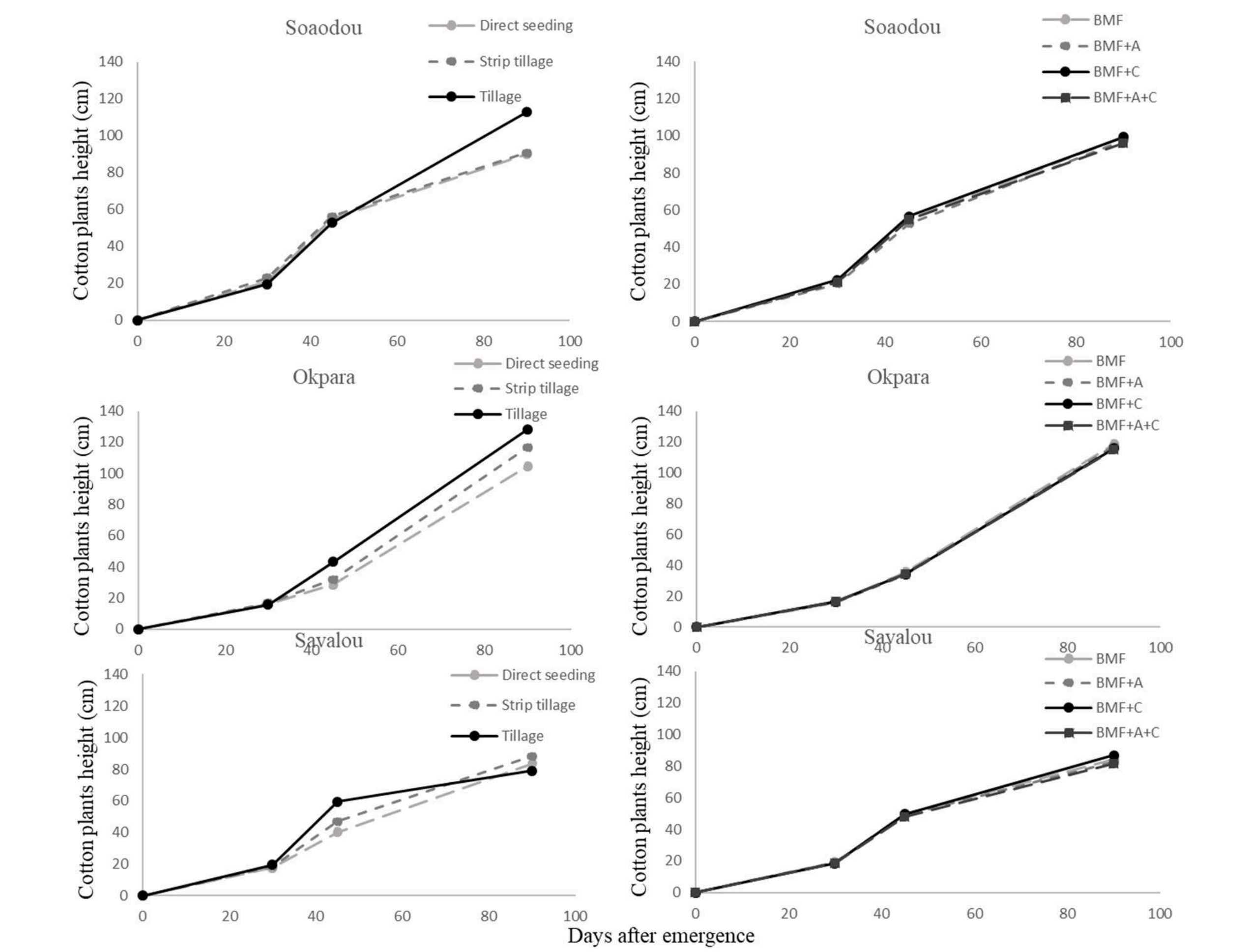

FIGURE 3
Cotton plant height at 30, 45 and 90 days after emergence. A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N).

Number of roots

At 40 days after emergence, the number of roots was significantly ($p < 0.05$) greater under conventional tillage than that under direct seeding or strip tillage only at Okpara, but not at Savalou or Soaodou (Figure 4). This trend is consistent with the variation observed in seed cotton yields (cf. "Seed cotton yield"). At Okpara, the number of roots was −52% under direct seeding compared with tillage, and there was no difference between strip tillage and direct seeding ($p > 0.05$). There was a significant interaction ($p < 0.05$) between soil preparation and site for the number of roots, while fertilizer regimes did not affect the number of secondary roots at any of the sites ($p > 0.05$).

Elbow frequency

Elbow frequencies differed broadly across sites and treatments (e.g., 91% for BMF+A+C conventional tillage in Okpara versus 4.4% for BMF direct seeding at Savalou), hampering the ability of the ANOVA to detect significant differences in an early transition to conservation agriculture in cotton-based cropping systems (Table 5). At Savalou, elbow frequencies were significantly lower (−87%) compared with those at Okpara and Soaodou. The same is true for soil preparation, which affected significantly ($p < 0.05$) the elbow frequency 40 days after emergence at the different sites (Table 5). Plants established under direct seeding and strip tillage had lower elbow frequencies compared with conventional tillage ($p < 0.05$). Fertilizer regimes affected root elbow frequencies at Soaodou and Okpara, but not at Savalou.

Discussion

Yield penalties

Our results suggest that direct seeding entails yield penalties in the order of roughly 6% to 20% compared with conventional tillage, in the first year of a transition to conservation agriculture (CA) in a cotton-based cropping system starting

TABLE 4 Belowground biomass (g plant^{-1}) in cotton based cropping systems at 40 days after emergence (means are followed by standard error).

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	1.41 ± 0.11 b	2.18 ± 0.19 a	1.49 ± 0.15 b
Strip till	1.47 ± 0.13 b	3.00 ± 0.35 a	1.86 ± 0.27 ab
Tillage	2.02 ± 0.23 a	2.23 ± 0.22 a	2.51 ± 0.31 a
Fertilizer regimes			
BMF	1.78 ± 0.29 a	2.47 ± 0.35 a	1.94 ± 0.35 a
BMF + A	1.69 ± 0.15 a	2.42 ± 0.32 a	2.12 ± 0.32 a
BMF + C	1.61 ± 0.22 a	2.52 ± 0.40 a	1.71 ± 0.30 a
BMF + A + C	1.47 ± 0.17 a	2.48 ± 0.25 a	2.05 ± 0.34 a
Soil preparation: Fertilizer regimes			
Direct seeding: BMF	1.13 ± 0.19 a	2.09 ± 0.60 a	1.43 ± 0.44 a
Direct seeding: BMF + A	1.67 ± 0.18 a	2.49 ± 0.16 a	1.53 ± 0.28 a
Direct seeding: BMF + C	1.18 ± 0.23 a	2.13 ± 0.29 a	1.32 ± 0.21 a
Direct seeding: BMF + A + C	1.67 ± 0.19 a	2.01 ± 0.53 a	1.69 ± 0.38 a
Strip till: BMF	1.46 ± 0.33 a	3.18 ± 0.76 a	1.93 ± 0.62 a
Strip till: BMF + A	1.32 ± 0.27 a	3.14 ± 0.66 a	2.20 ± 0.52 a
Strip till: BMF + C	1.18 ± 0.15 a	2.68 ± 0.46 a	1.84 ± 0.94 a
Strip till: BMF + A + C	1.30 ± 0.28 a	3.02 ± 0.22 a	1.49 ± 0.04 a
Tillage: BMF	2.76 ± 0.37 a	2.12 ± 0.34 a	2.48 ± 0.81 a
Tillage: BMF + A	2.08 ± 0.13 a	1.63 ± 0.41 a	2.64 ± 0.74 a
Tillage: BMF + C	1.82 ± 0.59 a	2.42 ± 0.56 a	1.99 ± 0.22 a
Tillage: BMF + A + C	1.43 ± 0.43 a	2.74 ± 0.32 a	2.96 ± 0.79 a
Soil preparation	0.01 ***	0.37 ns	0.00 ***
Fertilizers regimes	0.61 ns	0.98 ns	0.72 ns
Soil preparation: Fertilizers regimes	0.07 ns	0.97 ns	0.86 ns

**, ***significant at 5 % ($0.01 < P < 0.05$), and 1 % ($P < 0.01$), respectively; ns, not significant at $P \leq 0.05$. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

from moderately degraded soils (Table 1). Given the low average productivity across all treatments, such yield penalties were on average equivalent to roughly 100–400 kg less seed cotton yields per hectare. Yield differences varied between the experimental sites, and were widest at Okpara (Figure 2) and associated with differences in the number of roots and below-ground biomass. Although it was hypothesized that correcting soil fertility would reduce yield penalties associated with the transition to CA, virtually the opposite was observed. Adding compost and/or calcium phosphate to the basal fertilization regime increased the yield differences between tillage and no tillage, especially in sites where average yields were higher (up to 25% less yield under no tillage). The observed yield differences between sites can be partly explained by the different varieties used, according to local recommendations (varieties OKP 768 at Okpara and Savalou and ANG 956 at Soaodou were used), and by the environmental conditions during the experiment at the three sites.

Other studies reported short-term yield penalties in the transition to CA to be on either the neutral or negative trend (Vogel, 1993; Nyagumbo, 2002), have limited yield effects (Kitonyo et al., 2018; Rodenburg et al., 2020), or have substantial yield declines (Brouder and Gomez-Macpherson, 2014) under direct seeding (no tillage). The yield penalties can be explained by the immobilization of soil nutrients, poor germination, increased competition of weeds, stimulation of crop diseases, and poor drainage (Giller et al., 2011; Sommer et al., 2014; Bruelle et al., 2015, 2017). The negative effects of zero tillage have also been observed in soils, particularly poor in clays, which are widely distributed soils in semiarid environments with weak soil structure (Aina et al., 1991; Baudron et al., 2012; Corbeels et al., 2020). A global meta-analysis of the impact of the most prominent components of CA (no tillage and crop residue mulching) on yield was performed by Pittelkow et al. (2015), based on 5,463 paired yield observations, from 610 studies, across 48 crops and 63 countries. This analysis showed that no tillage reduces yields, yet this response is variable, and under certain conditions, no tillage can produce equivalent or greater yields than conventional tillage. When no tillage

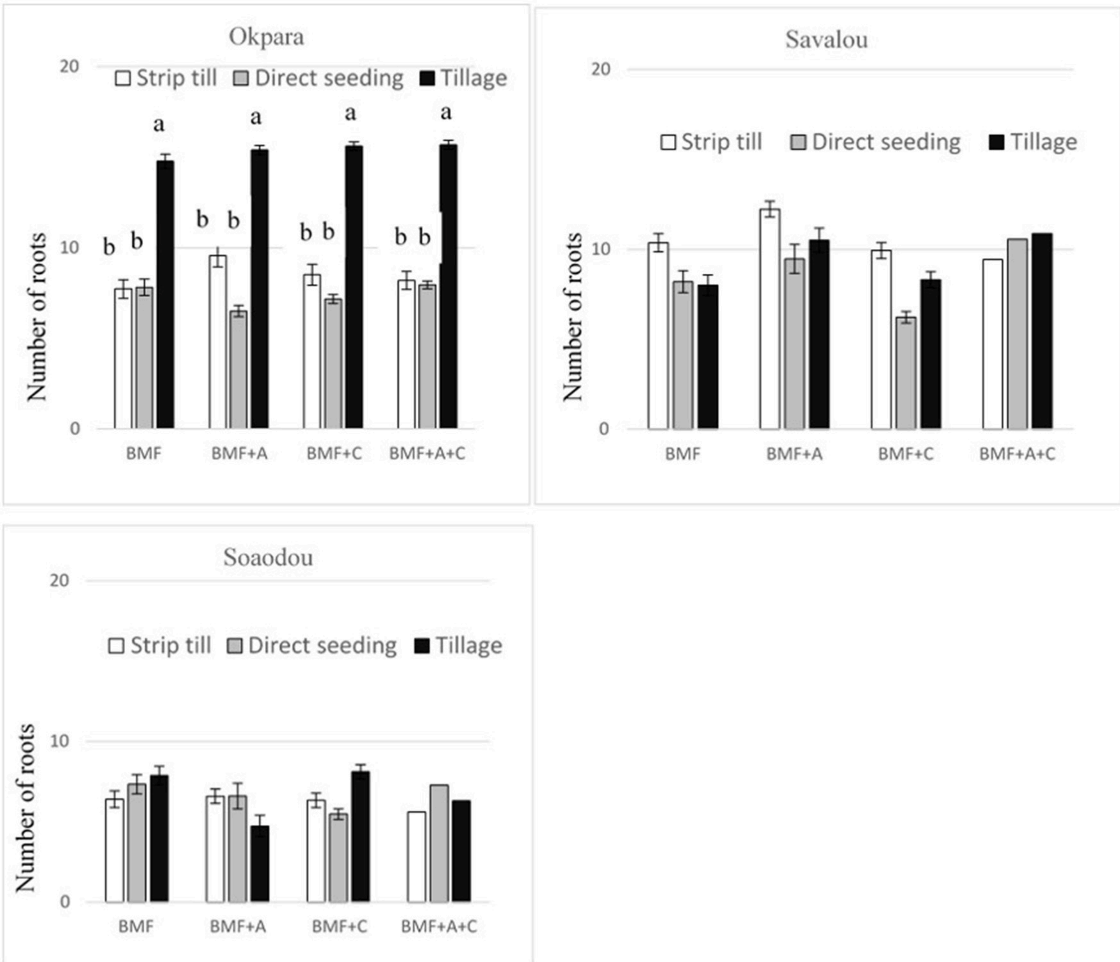

FIGURE 4
Number of roots at 40 days after emergence.

is combined with the other two principles of CA, namely, residue retention and crop rotation, its initial negative yield impacts are minimized (Corbeels et al., 2020). Büchi et al. (2018) reported similar results and highlighted the trade-offs between the preservation of agricultural soils, initially reduced yields, and weed management problems.

Beyond creating oxidative conditions in the soil that accelerates nutrient release and their assimilation by crops, tillage contributes to burying the weeds and incorporating in the soil organic matter lying on the surface, while making the soil loose, well-aerated, and easier for the roots to penetrate. In our experiment, tillage may have contributed to increasing deep water storage in the soil due to better infiltration of rainwater. The cotton plant has a dominant tap root system that requires loose soil to penetrate and meet its nutrient needs. These advantages, which may contribute to explaining the significant positive yield effect of tillage we observed during the first year, tend to disappear after years of practicing CA, as shown by different mid- to long-term studies (e.g., Lal, 1979; Mafongoya et al., 2016). Practicing minimum tillage instead of direct seeding resulted in higher average yields than with conventional tillage at Savalou and Soaodou, but not at Okpara, with positive yield differences ranging from extra 30 kg ha^{-1} to 70 kg ha^{-1} of seed cotton (i.e., 2–5% increase, Table 2). Minimum tillage, strip tillage in our case, appears as a reasonable compromise to minimize yield penalties in an early transition to CA.

Above- and below-ground biomass

Below- and above-ground biomass was significantly different across the three sites, mirroring the trends observed for seed cotton yields. Yet, soil preparation had stronger effects on seed cotton yields than on below- and above-ground cotton biomass production. Under direct seeding, below-ground cotton biomass was on average lower compared with that under conventional tillage, while above-ground biomass was

TABLE 5 Elbow frequency (%) on the taproot.

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	33.11 ± 5.53 b	27.22 ± 6.84 b	7.22 ± 2.24 b
Strip till	35.33 ± 4.22 b	24.44 ± 5.59 b	8.33 ± 2.19 b
Tillage	43.03 ± 3.96 a	90.00 ± 3.33 a	15.56 ± 2.51 a
Fertilizers regimes			
BMF	36.38 ± 5.52 ab	56.30 ± 11.82 a	11.11 ± 3.69 a
BMF + A	37.78 ± 7.44 ab	45.93 ± 12.19 b	9.63 ± 2.75 a
BMF + C	32.22 ± 4.37 b	40.74 ± 13.26 c	8.89 ± 2.22 a
BMF + A + C	44.17 ± 4.53 a	45.93 ± 11.89 b	11.85 ± 3.10 a
Soil preparation: Fertilizers regimes			
Direct seeding: BMF	34.00 ± 15.56 abcd	51.11 ± 15.56 b	4.44 ± 2.22 c
Direct seeding: BMF + A	33.33 ± 17.78 abcd	24.44 ± 17.78 c	6.67 ± 3.85 bc
Direct seeding: BMF + C	21.11 ± 5.88 b	11.11 ± 5.88 d	6.67 ± 3.85 bc
Direct seeding: BMF + A + C	50.00 ± 2.22 ab	22.22 ± 2.22 cd	11.11 ± 8.01 abc
Strip till: BMF	30.00 ± 16.67 cd	28.89 ± 19.75 c	8.89 ± 5.88 abc
Strip till: BMF + A	23.33 ± 10.00 bcd	24.44 ± 4.44 c	6.67 ± 3.85 bc
Strip till: BMF + C	37.78 ± 2.22 abcd	20.00 ± 11.55 cd	6.67 ± 3.85 bc
Strip till: BMF + A + C	44.44 ± 5.88 abc	24.44 ± 11.11 c	11.11 ± 5.88 abc
Tillage: BMF	42.22 ± 5.88 abc	88.89 ± 11.11 a	20.00 ± 7.70 a
Tillage: BMF + A	56.67 ± 10.00 a	88.89 ± 8.01 a	15.56 ± 5.88 ab
Tillage: BMF + C	37.78 ± 5.88 abcd	91.11 ± 4.44 a	13.33 ± 3.85 abc
Tillage: BMF + A + C	40.00 ± 10.18 abc	91.11 ± 5.88 a	13.33 ± 3.85 abc
Soil preparation	0.00 ***	0.00 ***	0.00 ***
Fertilizers regimes	0.00 ***	0.00 ***	0.10 ns
Soil preparation: Fertilizers regimes	0.00 ***	0.00 ***	0.03 **

, * significant at 5 % ($0.01 < P < 0.05$), and 1 % ($P < 0.01$), respectively; ns, not significant at $P \leq 0.05$. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N. A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

significantly lower only at the Savalou site. Roger-Estrade et al. (2011) associated the lower biomass observed under direct seeding with less soil porosity, which affects the development of the crop root system. Less below-ground biomass under direct seeding has been also associated with difficulty in rooting due to compact soils under no tillage (Labreuche et al., 2011). In our study, however, the average differences in root biomass in favor of tillage are largely driven by the results of the BMF and BMF+A treatments in both Soaodou and Savalou; when averages are calculated per single treatment (soil preparation × fertilization regime), we observed no significant differences in root biomass between any of the soil preparation and fertilization regimes (Table 4). On the contrary, a positive effect of tillage on the number of roots was only observed at Okpara (Figure 4). Thus, the proposed association between greater root development under tillage than under no tillage suggested by previous studies is not confirmed by our observations.

Other studies reported a neutral or negative effect of direct seeding on above-ground crop biomass compared with that of conventional tillage. A comparative study of the impact of conventional tillage and direct seeding showed that the biomass yields of the different varieties of rice were almost similar to both soil preparation methods (Jiang et al., 2021). Rühlemann and Schmidtke (2015) reported that direct seeding reduced significantly biomass production. Pale et al. (2021) in Burkina Faso also showed that conventional tillage had a more positive impact on millet biomass compared with direct seeding. Büchi et al. (2018) and Adimassu et al. (2019) also reported the highest above-ground biomass with conventional tillage and the lowest in direct seeding (no tillage). Similarly, our results show significant trends of greater biomass production under conventional tillage only when comparing grand means, but less clearly so when comparing individual treatments (soil preparation × fertilization regime; Table 3).

Effect of fertilizers

Under basal mineral fertilization, yield differences between tillage and no tillage tended to be narrow (2% to 10%), whereas they increased, especially in treatments when compost was added (10–25%; Figure 2). Fertilizer regimes affected significantly the seed cotton yields at Soaodou and Savalou when considering average yields. The absence of response to fertilizers on the other sites and treatment combinations can be explained by the quantity of compost (400 kg ha^{-1}) or calcium phosphate amendment (200 kg ha^{-1}) added to the soils. These quantities may not have been sufficiently large to induce short-term increases in seed cotton yields. Some studies showed a significant impact on the yields with the increase in compost (Adugna, 2016). Optimal rates of application to induce changes in yields are in the order of 4 t $ha^{-}$to 5 t ha^{-1}, but these quantities are not achievable by farmers. Fertilizer regimes did not affect the below-ground biomass at any of the experimental sites or across treatments, but they affected elbow frequencies at Soaodou and Okpara, but not at Savalou. Further studies should explore the relationship among fertilizer regimes, organic matter amendments, and no tillage, especially as this experiment evolves and soils get progressively restored in the next few years and include assessments of carbon sequestration and soil biological activity. The effects of compost and calcium phosphate amendments should be better assessed through a long-term study.

Conclusion

It can be concluded, from the preliminary findings of this study, that direct seeding led to 2–25% lower cotton yields compared with conventional tillage (i.e., a −20 kg ha^{-1} to −500 kg ha^{-1} difference), depending on fertilizer treatment, at all three experimental sites undergoing an early transition to conservation agriculture starting from moderately degraded soils. Such yield differences were wider when compost was added together with mineral basal fertilizers (4–25%) and narrower when only mineral fertilizers were added (2–10%). Contrary to what was hypothesized, the treatments adding compost and calcium phosphate led to better responses under conventional tillage than under no tillage. The observed yield differences can be largely attributed to the poorer rooting (root number and below-ground biomass) associated with no tillage as compared to the other treatments, leading to lower above-ground biomass and seed cotton yields. Increasing fertilizer inputs did not contribute to overcoming such yield declines under CA, and generally, there were no significant differences in productivity, above- or below-ground biomass, and root number across fertilizer regimes at any experimental location. Yet, the effects of soil preparation methods and fertilizer regimes should be assessed over longer periods of time, especially when starting from degraded soils as in this case. Short-term impacts on yields, production costs, or labor use are, however, important because they determine the attractiveness of producers to conservation agriculture and thus its potential for adoption. The impact of soil preparation on seed cotton yields was the widest at Okpara compared to the other sites, where soils are sandier and yields under conventional or strip tillage were substantially greater than the local average. Further research is needed to better understand the causes of such yield penalties and how to avoid them. Yet, considering the need for sustainable practices, in the context of severely degraded soils and poor productivity, such limited yield penalties under CA appear to be a reasonable trade-off. We will continue analyzing the present experiment for the next 5 years to identify cropping systems that may provide both short-term gains and long-term sustainability. From the preliminary results analyzed in this study, it appears that strip cropping may be an alternative yet less effective option to curtail soil degradation, but without yield penalties, and hence perhaps a practicable first step in the transition toward full conservation agriculture.

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

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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Understanding the differences in cultivated land protection behaviors between smallholders and professional farmers in Hainan Province, China

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Cultivated land protection and quality improvement have become inevitable requirements for alleviating ecological and environmental pressure and sustainable agricultural development. It is of practical significance to explore the differences and causes of cultivated land protection behaviors (CLPB) between smallholders and professional farmers for formulating targeted protection policies and improving their effectiveness. Based on 422 mango farmers' survey data in Hainan Province, this paper explored the internal and external characteristics between smallholders and professional farmers, and used the Fairlie decomposition method to compare and analyze the sources of differences in farmers' CLPB. The results showed that: (1) the CLPB of smallholders and professional farmers differ significantly; (2) the sources of differences in CLPB between smallholders and professional farmers are different, including differences in internal characteristics and differences in external characteristics; (3) differences in internal characteristics are the main cause of the differences in farmer's CLPB, and the contribution of differences in external characteristics was smaller, of which planting years, annual household income and planting scale are the top three factors. It is suggested that differential protection policies should be designed for smallholders and professional farmers, such as guiding smallholders to carry out large-scale operations and improve their organizational level, encouraging and guiding professional farmers to sign long-term contracts to stabilize the land tenure, and formulating subsidy policies for cultivated land protection.

KEYWORDS

cultivated land protection behaviors, difference, smallholders, professional farmers, Fairlie decomposition

Introduction

Cultivated land is an essential resource for human survival and development, which provides the basic guarantee for food production and security and plays a highly significant role in rural economic development and the ecological environment (Gomiero, 2016; Prăvălie et al., 2021). With increasing population size and urbanization, many high-quality cultivated lands have become urban lands, while cultivated land quality continues to decline due to low adoption of environmentally friendly agricultural production technologies, posing a severe challenge to increased agricultural demand and sustainability (Fazal, 2000; Zhou et al., 2021). At the same time, urbanization and excessive use of fertilizers and pesticides have brought about soil pollution and ecological degradation, further causing a decline in the quality of cultivated land (Jallow et al., 2017; Abass et al., 2018; Liu and Fang, 2021). Therefore, cultivated land protection and quality improvement have become inevitable requirements for alleviating ecological and environmental pressure and achieving sustainable agricultural development.

Since China's "reform and opening up," significant changes have occurred in socio-economic and cultivated land use. As one of the world's leading agricultural countries, China attaches importance to high-quality agricultural development, and cultivated land protection and quality improvement are important objectives of agricultural modernization (Lu et al., 2019; Su et al., 2019). The Chinese government has acted to protect cultivated lands and improve their quality. As early as 2015, the Chinese government put forward the strategy of "storing grain in the land and storing grain in the technology" and proposed to build 53 million hectares of high-standard cultivated land by 2020 to ensure national food security. The Ministry of Agriculture and Rural Affairs issued the Action Plan for the Protection and Improvement of Cultivated Land Quality in 2017 and the Key Policies for Strengthening and Benefiting Agriculture in 2021, which proposed new rules for cultivated land protection, including cultivated land protection subsidies, high-standard cultivated land construction, and land quality protection and improvement.

Under the household contract responsibility system in China, farmers are the basic unit of cultivated land use and most important participants and stakeholders of cultivated land protection, their land use behavior is the key to the improvement of cultivated land quality (Xue et al., 2021). Unlike the past, which relied mainly on many homogeneous smallholders to engage in agricultural production activities, the diversification of agricultural management subjects has gradually become a necessary basic feature of China's modern agricultural management system, such as the coexistence of family farms, large professional households and smallholders which has become a common phenomenon in China's agricultural production and different farmers play an important role in the protection of cultivated land quality (Lai et al., 2020). As the emerging body of agricultural production in China, professional farmers are mainly characterized by production specialization, which is reflected in the high level of technicalization, scale and organization in the production process. Unlike smallholders, professional farmers are modern farmers with higher educational knowledge level, modern civic competition, strong sense of democracy and cooperation and high anti-risk ability. Since the types of farmers are diversified, different farmers differ significantly in their characteristics and their CLPB may also be different (Lien et al., 2006). Therefore, it is significant to explore the differences in CLPB of different farmers and their influencing factors to formulate targeted cultivated land protection policies and improve their effectiveness.

From the existing studies, scholars have conducted rich research on farmers' CLPB and found that individual and household characteristics significantly affect their protection behavior (Ajewole, 2010; Das and Sahoo, 2012; Ma et al., 2018). However, few studies have been conducted to explain the differences and why different farmers have different CLPB, and only a few scholars have explored the protection behaviors of different farmer types, which is of reference significance to this paper. For example, some studies have shown that scattered smallholders have arbitrariness and blindness in agricultural production, with a general lack of knowledge about green production, and a poor understanding of the hazards of excessive fertilization and arable land protection (Mponela et al., 2016; Liu et al., 2021). Compared to smallholders, large-scale farmers are more inclined to adopt capital-intensive production methods, which are often associated with environmentally friendly technologies, due to labor shortage (Chen et al., 2022). Family farms with relatively better infrastructure conditions and stronger credit capacity are also more inclined to adopt green production practices to meet market demand and improve their agricultural products' quality and brand influence (Shang et al., 2021). This suggests that different types of farmers show significant differences in CLPB. In general, there are still relatively few comparative studies on the protection behaviors of different types of farmers, and the reasons for the differences in farmers' protection behaviors are still unclear.

In view of this, this paper takes mango farmers in Hainan Province as an example, and takes smallholders and professional farmers as research objects, which is different from previous studies that mostly compare smallholders with large-scale farmers or family farms. Based on defining and describing these two types of farmers, the Fairlie decomposition method is applied to explore farmers' differentiated CLPB and the main reasons so as to provide a reference basis for designing relevant incentive policies. This study contributes to the existing literatures in several ways. First, this paper takes professional farmers as the research object, which makes up for the shortage of previous researches focusing on smallholders, large-scale farmers, and family farms. Second, the differences in CLPB between smallholders and professional farmers and the generation mechanism are clarified theoretically, which enriched the theoretical research on the farmers' environmental protection behaviors. Third, while most of the existing studies focus on farmers growing field crops, this paper explores the cultivated land protection behaviors of fruit growers and broadens the research boundary.

The rest of the paper is organized as follows: in Section Conceptual framework, a conceptual framework related to farmers' cultivated land protection behaviors is developed. Section Materials and methods introduces data sources, sampling descriptions, and modeling methods. A results section follows showing the empirical results. Discussions and policy implications are presented in Section Discussion and the paper ends with conclusion in Section Conclusions.

Conceptual framework

There are two main types of mango farmers in Hainan Province: smallholders and professional farmers. The basic situation of the two types of farmers is shown in Table 1. There are significant differences in characteristics between smallholders and professional farmers, which can be categorized into two aspects: on the one hand, there are differences in external characteristics, which mainly refer to differences in socio-economic characteristics at the household level; on the other hand, there are differences in internal characteristics, mainly referring to the differences farmers' identity, adaptability, responsibility, and sense of belonging.

Smallholders

Smallholders are engaged in agricultural production based on family business units, which is the typical form of mango planting in Hainan. From the national level, the "big country with small farmers" is still the basic national condition of China; smallholders account for more than 98%, and operating cultivated land area accounts for 70% of the total cultivated land area, which is the most basic main body of China's agricultural production.[1] Most smallholders from the formation of farmers are Hainan local farmers whose labor input is mainly family members. The education level of smallholders is relatively low, and they tend to base their agricultural production on their own experience, and their production technology level is relatively low. In terms of land characteristics, smallholders generally operate on a small scale, and the degree of land fragmentation is relatively high (Alemu et al., 2017). In terms of the organizational characteristics of farmers, smallholders often show a lack of cooperation or low efficiency of cooperation among themselves, a low degree of organization, and a generally weak ability to resist natural and market risks (Li et al., 2021).

Professional farmers

Scholars have not reached a consensus on the definition and classification of professional farmers (Zhao et al., 2019). According to Zhong et al. (2018), this paper selects agricultural reclamation farmers with vocational characteristics as representatives of professional farmers for analysis. Therefore, professional farmers in this paper refer to growers affiliated with state farms and contract farm land for specialized production by their households. This type of farmer's business form is based on state-owned land and the implementation of the joint production contract as the basis for family farm production under the leadership of state farms. Established in 1952, Hainan State Farm has 47 state farms, making it the third largest farm in China after Xinjiang Production and Construction Corps and Heilongjiang State farms, which has made important contributions to driving and radiating the economic and social development of the surrounding rural areas. In the 1990's, through the reform of the two-tier management system, the state-owned farms established the land contract management right, and the farm workers contracted the farm land for production, thus forming professional farmers. At the national level, the total number of professional farmers has exceeded 20 million by 2021, becoming the emerging main body of China's agricultural production. From the perspective of the formation of farmers, professional farmers are mostly migrants who entered Hainan during the construction of state-owned farms in 1960's and 1970's. In terms of the technical level, since most family members of professional farmers are farm workers, their professional technology and mechanical equipment level are relatively higher (Liu et al., 2021). In terms of land characteristics, professional farmers also contract farm state-owned land through the family joint production responsibility system and tend to carry out agricultural production on a larger scale. In terms of the organizational characteristics of farmers, professional farmers are backed by state-owned farms and tend to be organized by the farms on production materials purchase, technology and variety promotion, and agricultural products marketing, so the degree of organization of professional farmers is higher compared to smallholders.

Since domestic and foreign studies have fully discussed the influence of external characteristics of farmers (such as gender, age, and ethnicity) on CLPB (Ros-Tonen et al., 2019; Belachew et al., 2020; Henriksson et al., 2021), this paper focus on the analysis of farmer's internal differences and how they affecting farmers' CLPB. Based on the descriptions of the two types of farmers above, it is clear that their basic conditions differ significantly. We believe that farmers' different internal characteristics can lead to differentiated cultivated land protection behaviors mainly through the following mechanisms: the first is the heterogeneity of the formation period, which may lead to different geographical identities and adaptations. Smallholders, as local farmers in Hainan, were formed at an earlier period, while professional farmers, as outsiders who came to Hainan during the establishment of state-owned farms, were formed at a later period compared to smallholders, so there are large differences in the geographical identity and adaptability of the two types of farmers (Cai et al., 2017). Second, the technical level of professional farmers is higher than that of smallholders, which may be due to inherent differences in production philosophy (Wang et al., 2021). Third, the nature and status of land ownership differ between smallholders and professional farmers, and thus the sentiment and dependence on land may differ, which may further affect farmers' sense of responsibility for cultivated land protection (Chen, 2013; Ayamga et al., 2016). Fourth, the degree of organization of village collectives and state farms differs, which may affect farmers' access to production materials and marketing of agricultural products, but may ultimately affect their sense of belonging (Mosimane et al., 2012). Base on the above analysis, it is clear that the differences in characteristics of different types of farmers may lead to the internal differences in farmers' characteristics of identity, adaptability, production philosophy, responsibility, and sense of belonging, which may further influence their behavioral attitudes, subjective norms, and perceived behavioral control (Yao et al., 2016), and ultimately lead to differential CLPB (as shown in Figure 1).

TABLE 1 Characteristics of smallholders and professional farmers.

Basic characteristics	Smallholders	Professional farmers
Formation period	Earlier	1990's
Technical level	Low	High
Land ownership	Contracting village collective land	Contracting state farm land
Land scale	Small	Large
Land fragmentation degree	High	Low
Organization mode	Village collectives	State farm
Organizational degree	Lower	Higher

Materials and methods

Data source

The data in this paper come from the field research conducted by the research team in 2020 in Dongfang, Ledong, and Sanya cities of Hainan Province for mango growers, as shown in Figure 2. Mango as an important tropical fruit, coupled with Hainan's suitable light and heat conditions, gradually become one of the main products of Hainan agriculture. The sample was selected because Ledong,

1 Data from the Third Agricultural Census of China.

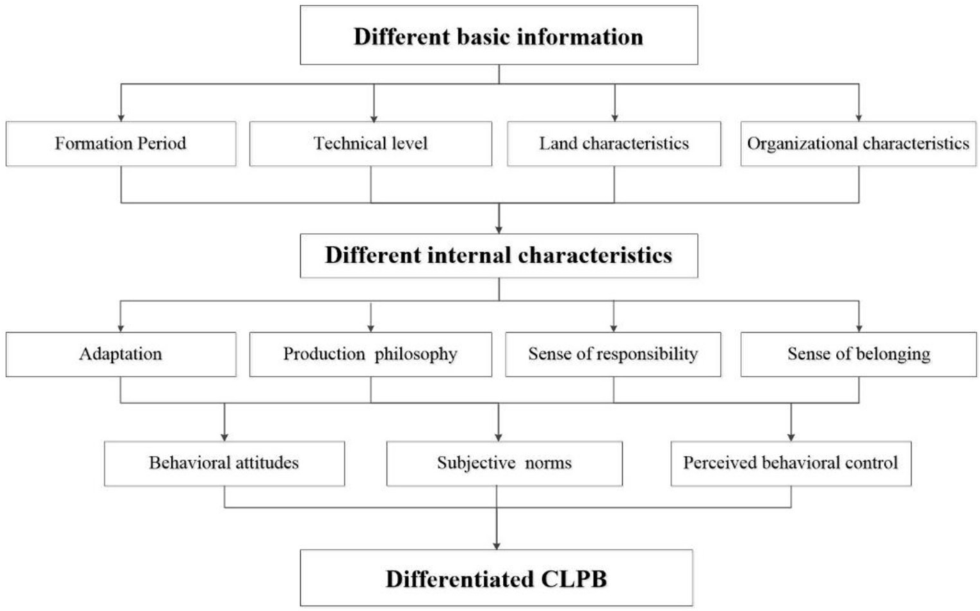

FIGURE 1
The formation of internal characteristics differences and their influence on farmers' CLPB.

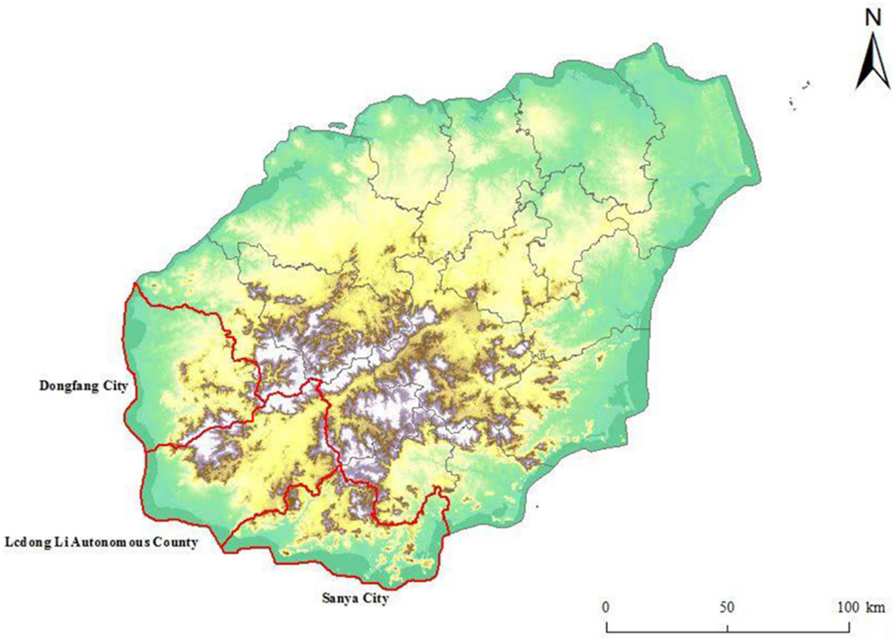

FIGURE 2
Study area.

Dongfang, and Sanya are important mango planting bases in Hainan. At the end of 2019, the mango planting area in these three cities and counties accounted for 86.5% of the total planting area in Hainan Province, which is representative of the study. The survey used a combination of staged sampling and a random sampling method. In the first stage, three townships were selected from each city or county; in the second stage, two to three administrative villages were randomly selected from each township; in the third stage, 20–25 mango growers were randomly selected as survey subjects. The questionnaire survey mainly includes basic information about individual farmers and families, mango production and operation, etc. A total of 449 questionnaires were distributed, 27 invalid and incomplete questionnaires were excluded, and finally, 422 valid questionnaires were obtained, with an efficiency rate of 93.99%.

The basic characteristics of the sample growers are shown in Table 2. Mango growers whose household heads are over 50 years old account for 54.97% of the total sample, and those whose heads are 35–50 years old account for nearly 40%; the education level of household

TABLE 2 Basic characteristics statistics of the sample farmers.

Variables	Category	Observations	Percentage
Age (year)	20–35	24	5.69%
	36–50	166	39.34%
	51–65	213	50.47%
	>65	19	4.50%
Education (year)	≤6	140	33.17%
	7–9	212	50.24%
	10–12	56	13.27%
	≥13	14	3.32%
Annual household income (10,000 yuan)	≤10	246	58.29%
	10–20	97	22.99%
	20–30	51	12.09%
	30–40	10	2.37%
	>40	18	4.27%
Planting years (year)	≤10	117	27.73%
	10–20	190	45.02%
	20–30	105	24.88%
	30–40	10	2.37%
Share of agricultural labor (%)	0–0.25	7	1.66%
	0.25–0.5	78	18.48%
	0.5–0.75	46	10.90%
	0.75–1	291	68.96%
Planting scale (mu)	≤10	132	31.28%
	10–20	137	32.46%
	20–30	73	17.30%
	30–40	25	5.92%
	>40	55	13.03%

heads is mostly junior high school or below, accounting for 83.42%, but there are a few household heads with a college education or above. 8.29% of mango farmers have an annual household income of <100,000; 68.96% of the full sample are mango farmers with an agricultural labor force ratio higher than 0.75, indicating that most of the surveyed sample are mainly engaged in agriculture; 72.27% of mango farmers have been cultivating for more than 10 years, indicating that most of the sample have long-term cultivation experience; 63.74% of mango farmers have a planting scale of fewer than 20 mu, and 13.03% have a planting scale of more than 40 mu. The sample generally shows good representativity.

Variable settings

Explained variable

The explained variables in this paper are the protection behaviors of mango farmers, which correspond to the questions "Do you use organic fertilizer?" and "Do you use soil testing and fertilization technology?" If the respondent farmers answered in the affirmative, they were considered to have CLPB and the explanatory variable was assigned a value of 1, otherwise a value of 0. It should be noted that the organic fertilizer referred to is a commercial organic fertilizer made from livestock and poultry manure, animal and plant residues, and other resources after fermentation and maturation. The soil testing and fertilization technology are tested by enterprises, agricultural stores, soil fertilization institutes, or fruit stations, mainly including the five steps of "soil testing, formulation, fertilization, supply, and guidance."

Explanatory variable

Based on existing studies, we selected personal characteristics of household heads, household characteristics, and production and management characteristics as the main explanatory variables affecting mango farmers' CLPB, as shown in Table 3.

Firstly, the household head, as the leading decision-maker in household production and operation, has an important influence on CLPB. Personal characteristics of the household head, such as age, education level, perception of fertilizer pollution, planting years, and internet use, often influence the decision-making (Adnan et al., 2017; Tey et al., 2017; Rahman and Zhang, 2018; Haile et al., 2019; Ma et al., 2020).

Second, the agricultural labor proportion reflects farmers' dependence on agricultural production. Households with a higher proportion of agricultural labor rely more on agricultural production, which may prompt them to apply organic fertilizers that help improve cultivated land quality (Waithaka et al., 2007; Noll et al., 2014; Teshome et al., 2016). Annual household income directly impacts farming households' access to organic fertilizers, and in general, households with high-income level have more capital to invest in green production (Nastis et al., 2019). At the same time, farmers' CLPB is also easily influenced by social relationships and surrounding neighbors, for example, farmers with more interactions and stronger neighborhood effects are more likely to obtain information about cultivated land protection and thus promote their implementation of CLPB (Tsusaka et al., 2015; Zeweld et al., 2018; Qiao et al., 2022). Therefore, four variables, namely the proportion of agricultural labor, annual household income, number of interactions, and neighborhood effect, were selected to investigate the effects of household characteristics.

Furthermore, farmers with larger planting scale and more plots of cultivated land may need to invest more labor and transportation costs if they implement CLPB, which may negatively affect their CLPB to a certain extent (Kaliba et al., 2000). Extension services and support subsidies provide technical and financial support to farmers, respectively, which can reduce the pressure on farmers to conserve their land and thus increase their likelihood of implementing CLPB (Boz, 2016; Zhang et al., 2022). Therefore, this paper also selects the variables of planting scale, number of land plots, extension services and support subsidies to study the influence of production and management characteristics on their CLPB (Abhilash and Singh, 2009; Qiao et al., 2022).

Model settings

The Oaxaca-Blinder decomposition method ("O-B decomposition method") is used by scholars at home and abroad

TABLE 3 Variable definition and descriptive statistics.

Variables	Definition	Mean	S.D.
Explained variable			
CLPB	Whether to apply organic fertilizer or use soil testing and fertilization technology (0 = no, 1 = yes)	0.346	0.476
Explanatory variable			
Age	The age of the household head (years)	51.057	9.083
Education	Education level of the head of household (Primary school and below = 1; Secondary = 2; High School = 3; College and above = 4)	1.867	0.762
Chemical fertilizer pollution cognition	Whether there is a perception that excessive use of fertilizers pollutes the environment (0 = no, 1 = yes)	0.339	0.474
Planting years	Mango growing years (years)	17.045	7.366
Internet usage	Whether to use a computer to access agricultural information (0 = no, 1 = yes)	0.291	0.455
Share of agricultural labor	The proportion of agricultural labor to household labor (%)	0.848	0.237
Annual household income	Total income of mango cultivation in a year (10,000 yuan)	13.057	12.377
Number of interactions	Number of daily commuters (people)	18.194	18.321
Neighborhood effects	Availability of help from neighbors (1 = never/rarely, 2 = occasionally/rarely, 3 = average, 4 = often/more, 5 = frequently/a lot)	3.483	1.209
Planting scale	Mango planting area (mu)	22.712	18.753
Number of land plots	Number of plots of land you own (blocks)	2.405	2.178
Extension services	Whether or not they have received related to mango cultivation promotion Extension (0 = no, 1 = yes)	0.555	0.498
Support subsidies	Whether support or subsidy policies related to mango cultivation (0 = no, 1 = yes)	0.085	0.280

to analyze the sources of difference between groups. The method can decompose the sources of difference between groups into observable differences in characteristics (the explainable part) and unobservable differences in coefficients (the unexplainable part), and then determine the main causes of difference (Blinder, 1973; Oaxaca, 1973). However, the early O-B decomposition was based on linear regression models with continuous explained variables and did not apply to models with discrete explained variables. In view of this, Nielsen and Bauer extended the O-B decomposition to discrete explained variable models (Nielsen, 1998; Bauer and Sinning, 2008), making it applicable to the decomposition of Logit models. However, the model can only analyze the explainable component as a whole and fails to refine the contribution of differences to specific explanatory variables. Further, Fairlie improved the extended O-B decomposition to allow the analysis of the extent to which each explanatory variable in the explainable component contributes to the difference, which is also known as the "Fairlie decomposition" (Fairlie, 2005). The explained variable in this paper is "whether to adopt CLPB," which is a discrete binary variable and thus requires the Fairlie decomposition method. Firstly, this paper uses a binary logit model to estimate the factors influencing farmers' CLPB. The specific model form is as follows:

$$y_i = F(z_i\delta) \tag{1}$$

In Equation 1, the y_i is the explained variable (whether to adopt CLPB); F denotes the cumulative distribution function of the logistic distribution; z_i is a linear combination of explanatory variables, mainly including personal characteristics of household heads, household characteristics, and production and management characteristics; δ is the estimated coefficients affecting the explained variables. The probability distribution of farmers' CLPB can be expressed as follows:

$$P_i = P_r(y_i = 1|z_i) = \frac{Exp(z_i\delta)}{1 + Exp(z_i\delta)} \tag{2}$$

Further, based on the estimation results of the Logit model, an extended O-B decomposition was used to perform a primary decomposition, which decomposes the sources of differences in CLPB between the two types of farmers into an explainable part (differences in external characteristics as referred to in the text) and an unexplainable part (differences in internal characteristics as referred to in the text). The decomposition method is as follows:

$$\overline{Y_p} - \overline{Y_s} = E + U = \left[\sum_{i=1}^{N_p} \frac{F(Z_{pi}\widehat{\delta^p})}{N_p} - \sum_{i=1}^{N_s} \frac{F(Z_{si}\widehat{\delta^p})}{N_s}\right] + \left[\sum_{i=1}^{N^s} \frac{F(Z_{si}\widehat{\delta^p})}{N_s} - \sum_{i=1}^{N^s} \frac{F(Z_{si}\widehat{\delta^s})}{N_s}\right] \tag{3}$$

In Equation 3, $\overline{Y_p}$ and $\overline{Y_s}$ represents the mean value of CLPB of Professional Farmers and smallholders, respectively; $\overline{Y_p} - \overline{Y_s}$ indicates the difference in CLPB between professional farmers and smallholders; Z_{pi} and Z_{si} denotes the explanatory variables corresponding to professional farmers and smallholders, respectively; N_p and N_s represents the sample size of professional farmers and smallholders respectively; $\widehat{\delta^p}$ and $\widehat{\delta^s}$ are the estimated coefficients of the explanatory variables for the professional farmers and smallholders, respectively. The difference between the first two terms on the right-hand side of Equation 3 is the explainable part of the difference in CLPB between professional farmers and smallholders, i.e., the difference in CLPB caused by differences in the personal, household and production characteristics of the household head; the difference between the last two terms is the unexplainable part of the difference in CLPB between professional farmers and smallholders. An alternative expression for Equation 3 is as follows:

$$\overline{Y_p} - \overline{Y_s} = E + U = \left[\sum_{i=1}^{N_p} \frac{F(Z_{pi}\widehat{\delta^s})}{N_p} - \sum_{i=1}^{N_s} \frac{F(Z_{si}\widehat{\delta^s})}{N_s}\right] + \left[\sum_{i=1}^{N_p} \frac{F(Z_{pi}\widehat{\delta^p})}{N_p} - \sum_{i=1}^{N_p} \frac{F(Z_{pi}\widehat{\delta^s})}{N_p}\right] \quad (4)$$

The difference between Equations 3 and 4 is the choice of a different benchmark. Equation 3 is based on the estimated coefficients $\widehat{\delta^p}$ for professional farmers, while Equation 4 is based on the estimated coefficients $\widehat{\delta^s}$ for smallholders. It can be seen that the choice of different benchmarks may yield different analytical results, with the problem of index benchmarking, i.e., whether the estimated coefficients of smallholders or professional farmers are used as a benchmark, the unexplained component is over- or underestimated. Therefore, this paper draws on the solution proposed by Newmark to calculate the estimated coefficients $\widehat{\delta^*}$ for the entire sample with the following equation:

$$\overline{Y_p} - \overline{Y_s} = E + U = \left[\sum_{i=1}^{N_p} \frac{F(Z_{pi}\widehat{\delta^*})}{N_p} - \sum_{i=1}^{N_s} \frac{F(Z_{si}\widehat{\delta^s})}{N_s}\right] + \left[\sum_{i=1}^{N_p} \frac{F(Z_{pi}\widehat{\delta^p})}{N_p} - \sum_{i=1}^{N_p} \frac{F(Z_{pi}\widehat{\delta^*})}{N_p}\right] \quad (5)$$

Finally, to obtain the contribution of each explanatory variable in the explainable component to the source of differences, the paper further decomposed according to Fairlie. For the sake of exposition, it is assumed that N_p=N_s and there are only two explanatory variables in the explainable part X^A and X^B. Then the differences contribution of the explainable part of Equation 5 is expressed as Equation 6:

$$E = \frac{1}{N_p} \sum_{i=1}^{N_p} \left[F(\widehat{c}^* + X_{pi}^A\widehat{\delta}^{A*} + X_{pi}^B\widehat{\delta}^{B*}) - F(\widehat{c}^* + X_{si}^A\widehat{\delta}^{A*} + X_{si}^B\widehat{\delta}^{B*})\right] \quad (6)$$

In Equation 6, $\widehat{c}^*$ is the full sample of farmers estimated coefficient of the constant term c in the Logit model. It can be obtained by decomposition calculation: variables X^A and X^B respective contributions to the sources of variation are as follows (Fagbamigbe et al., 2021):

$$E_A = \frac{1}{N_p} \sum_{i=1}^{N_p} \left[F(\widehat{c}^* + X_{pi}^A\widehat{\delta}^{A*} + X_{pi}^B\widehat{\delta}^{B*}) - F(\widehat{c}^* + X_{si}^A\widehat{\delta}^{A*} + X_{pi}^B\widehat{\delta}^{B*})\right] \quad (7)$$

$$E_B = \frac{1}{N_p} \sum_{i=1}^{N_p} \left[F(\widehat{c}^* + X_{si}^A\widehat{\delta}^{A*} + X_{pi}^B\widehat{\delta}^{B*}) - F(\widehat{c}^* + X_{si}^A\widehat{\delta}^{A*} + X_{si}^B\widehat{\delta}^{B*})\right] \quad (8)$$

Results

Analysis of the differences in the characteristics of smallholders and professional farmers

To further compare the differences in CLPB and each explanatory variable between smallholders and professional farmers, descriptive statistics and mean difference tests were conducted separately for the two types of farmers, as shown in Table 4. It can be seen that the mean values of CLPB between smallholders and professional farmers are 0.292 and 0.403, respectively, and are significant at the 5% level. In terms of the personal characteristics of the household head, there were significant differences in planting years between the two types of farmers at a significant level of 1%, while there were no significant differences in age, education, chemical fertilizer pollution cognition, and internet usage. In terms of household characteristics, there were significant differences in annual income between the two types of farmers at a significant level of 1%, while the share of agricultural labor, number of interactions, and neighborhood effects did not differ significantly. In terms of the production and management characteristics, there were significant differences in planting scale at a significant level of 1%, while there were no significant differences in the number of land plots, extension services, and support subsidies.

Analysis of factors influencing farmers' CLPB

This paper used Stata (Version 15.0, created by Stata Corp LLC in Texas, USA) software for model estimation, as shown in Table 5. To exclude the possible co-linearity problem among the explanatory variables, this paper adopts the variance inflation factor method to conduct the multiple co-linearity tests. The test results show that each variable's Vif (variance inflation factor) is <5, indicating no problem with multicollinearity.

Firstly, in terms of personal characteristics, the education level has a significant positive effect on CLPB of smallholders, professional farmers and full sample farmers, probably because more educated farmers have a higher awareness of the ecological services, social security value, as well as a stronger ability to learn land protection techniques. Planting years had a significant positive effect on CLPB for the smallholders and total sample farmers, while age, chemical fertilizer pollution cognition and internet use were not significant in the estimated coefficients for all three groups of samples, indicating that they had no significant effect on CLPB. Secondly, in terms of the household characteristics, the share of agricultural labor and annual income had a significant positive effect on CLPB of smallholders and total sample farmers, which indicated that farmers with more agricultural labor in the household and higher total income had more positive CLPB (Nastis et al., 2019). Neighborhood effect had a significant positive effect on CLPB of professional farmers, while number of interactions was not significant in the estimated coefficients of all three sample groups. Furthermore, in terms of production and management characteristics, planting scale has a significant negative effect on CLPB of smallholders, professional and full sample farmers, the possible reason is that the larger the planting scale, the more labor and transportation costs may be required to implement protection behavior, which negatively affects their

TABLE 4 Descriptive statistics and mean difference test of farmers' characteristics.

Variables	Smallholders		Professional farmers		Difference
	Mean	S.D.	Mean	S.D.	
CLPB	0.292	0.456	0.403	0.492	0.111**
Age	50.565	9.732	51.573	8.342	1.008
Education	1.829	0.797	1.908	0.723	0.079
Chemical fertilizer pollution cognition	0.315	0.466	0.364	0.482	0.049
Planting years	15.940	8.053	18.204	6.385	2.264***
Internet usage	0.264	0.442	0.320	0.468	0.056
Share of agricultural labor	0.848	0.238	0.849	0.237	0.000
Annual income	10.301	11.109	15.947	12.991	5.646***
Number of interactions	17.556	18.924	18.864	17.689	1.309
Neighborhood effects	3.394	1.264	3.578	1.144	0.184
Planting scale	18.376	15.696	27.258	20.573	8.882***
Number of land plots	2.546	1.749	2.257	2.548	−0.289
Extension services	0.532	0.500	0.578	0.495	0.045
Support subsidies	0.102	0.303	0.068	0.252	−0.034

***, **Indicate significance at the 1 and 5% levels, respectively.

TABLE 5 Results of the analysis of factors influencing the CLPB.

Variables	Smallholders		Professional farmers		Full sample	
	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
Age	0.013	0.018	−0.020	0.020	0.000	0.013
Education	0.490**	0.208	0.386*	0.222	0.429***	0.144
Chemical fertilizer pollution cognition	0.177	0.354	0.298	0.326	0.283	0.229
Planting years	0.041*	0.022	0.019	0.026	0.030*	0.016
Internet usage	−0.389	0.397	0.304	0.352	−0.101	0.249
Share of agricultural labor	1.386*	0.744	0.617	0.705	0.891*	0.485
Annual income	0.040**	0.018	0.016	0.017	0.027**	0.012
Number of interactions	0.010	0.009	0.010	0.009	0.009	0.006
Neighborhood effects	−0.140	0.136	0.450***	0.163	0.111	0.096
Planting scale	−0.025*	0.014	−0.024**	0.011	−0.015**	0.008
Number of land plots	−0.126	0.105	0.108	0.066	0.006	0.052
Extension services	0.121	0.348	0.796**	0.333	0.438*	0.231
Support subsidies	0.119	0.569	−0.078	0.612	0.013	0.404
Constant term	−3.777***	1.374	−3.349**	1.547	−3.618***	0.962
Sample size	216		206		422	

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

protection behavior to some extent (Kaliba et al., 2000). Extension services significantly positively affected the CLPB of professional farmers and full sample of farmers. It may be due to the fact that professional farmers with well-developed infrastructure can apply the technologies provided by extension services more efficiently in practice, while smallholder farmers may lack the conditions for application (Liu et al., 2021). The number of land plots and support subsidies were insignificant in the estimated coefficients of all three groups of samples. It may be because farmers with many land plots are more dependent on agricultural production, prompting them to improve cultivated land quality, which offsets inconvenient transportation's negative impact on farmers' CLPB. In addition, the capital, time and labor costs of CLPB are very high, and limited support subsidies can hardly cover the costs for farmers, so subsidies have no significant impact.

It can be seen that there are significant differences in the external characteristics that influence the CLPB of smallholders and professional farmers. This suggests that the causes of differences in CLPB between the two types of farmers are different in their explainable parts (differences due to external characteristics). Further discrepancy decomposition is required to explore the reasons for the above discrepancies.

Decomposition of differences in CLPB

In this paper, we decompose the causes of the difference in CLPB between smallholders and professional farmers by the Fairlie decomposition method. The method requires an equal sample size in the comparison group, using the farmer category with the smaller sample size in the comparison group as a benchmark, and an equal subsample from the farmer category with the larger sample size in the comparison group for analysis by random sampling. To avoid over-reliance of the analysis results on a single sub-sample, each group of comparisons in this paper was repeated 100 times as described above. In addition, when using the Fairlie decomposition method for analysis, the same variable may be estimated with slightly different results depending on the order in which it is placed. To solve the above problem, we randomly collected 100 sets of subsamples while randomly sorting the variables 100 times, then decomposed them and calculated the mean value of the different contributions of each variable as the final result. Table 6 reports the specifics of the decomposition of differences in CLPB between the two types of farmers.

In the comparison between smallholders and professional farmers, the total difference between the two types of farmers' CLPB was 0.112, using the estimated coefficient of the full sample as a benchmark. The explainable part of the difference was 0.029, accounting for 26.11%; the unexplainable part was 0.083, accounting for 73.89%. Further decomposition of the explainable part shows that planting years, annual income and planting scale are the main factors influencing the difference in CLPB between the two types of farmers, and their contribution rates are above 10%, among which planting years and annual income increase the difference in CLPB between the two types of farmers by 11.03 and 27.34%, respectively, and planting scale decreases the difference in CLPB between the two types of farmers by 30.77%. From the above analysis results, it is clear that the difference in internal characteristics accounts for 73.89% of the difference in CLPB between the two types of farmers. In comparison, the difference in external characteristics accounts for 26.11%. The contribution of planting years, annual income, and planting scale are greater because professional farmers have more experience in planting, higher household capital endowment, and larger planting scale.

Robustness test

In order to verify the reliability of the above findings, the robustness test was conducted by replacing the index benchmark. The estimated coefficients of smallholders and professional farmers were used as the new index benchmark of the model to replace the index benchmark in the original model, and then the regression analysis was conducted again. The results are shown in Table 6. The estimation results using the coefficients of smallholders and professional farmers as benchmarks are similar to those of the full sample of farmers, indicating that the above results are robust.

Discussion

Protecting the quality of cultivated land is an inevitable requirement for alleviating ecological and environmental pressure and achieving sustainable agricultural development. For this reason, the Chinese government has introduced many policies on cultivated land protection. Effectively implementing cultivated land protection policies depends greatly on farmers' acceptance of the policies. However, various types of farmers in China have different characteristics, and their acceptance of cultivated protection policies differs. As representatives of agricultural operation subjects, smallholders, and professional farmers play an important role in protecting cultivated land quality. Therefore, it is essential to study the differences in CLPB and the reasons between smallholders and professional farmers to formulate differentiated protection policies.

Previous studies on farmers' cultivated land protection provide a good reference for this paper. However, two points remain to be explored: first, there are still relatively few comparative studies on different types of farmers' CLPB, and the reasons for the differences in their behaviors are still unclear; second, in the existing studies, scholars have more often explored the differences among smallholder and large-scale farmers, but relatively few studies have been conducted on professional farmers, who are an important component. Therefore, this paper focuses on the differences and reasons of CLPB between smallholders and professional farmers. It is found that smallholders' and professional farmers' external and internal characteristics are different, which leads to the great difference in CLPB. Secondly, this paper discusses the influencing factors of CLPB, and analyzes the factors that cause the difference and their contributions.

Based on the main findings, this paper puts forward the following policy recommendations: (1) As the most basic subject of agricultural production in China, smallholders' participation in cultivated land protection is currently low, so attention should be paid to the design of cultivated land protection policies for smallholders to guide them to implement large-scale operation and improve their organization. At the same time, smallholders' awareness of cultivated land protection can be improved by increasing the propaganda related to cultivated land protection. (2) Due to the particularity of land lease, professional farmers have weak awareness of farmland protection, so they should be guided to sign long-term contracts to stabilize the land use right. Professional farmers should also be treated as local residents regarding agricultural subsidies, technology promotion, children's education and other aspects, to improve regional identity and adaptability, and ultimately improve their CLPB. (3) It is necessary to formulate subsidy policies related to cultivated land protection, provide differentiated compensation to smallholders and professional farmers, and effectively improve the endogenous power of cultivated land protection. In addition, farmers' literacy and agricultural technology can be improved through rural night schools, short-term training, and internet usage.

Additionally, several aspects are worthy of further discussion for the current work. For example, other types of farmers could be included for comparative studies, or more factors influencing farmers' CLPB can be included. In view of this, a more completed and targeted questionnaire could be designed in future studies to explore more in-depth.

TABLE 6 Decomposition of differences in CLPB.

Variables		Full sample as a benchmark		Smallholders as a benchmark		Professional farmers as a benchmark	
		Difference	Percentage	Difference	Percentage	Difference	Percentage
Explainable part	Age	0.000	−0.17%	0.002	1.75%	−0.002	−1.39%
	Education	0.008	6.84%	0.006	5.67%	0.008	7.07%
	Chemical fertilizer pollution cognition	0.003	2.47%	0.001	1.34%	0.003	2.84%
	Planting years	0.012	11.03%	0.016	13.95%	0.007	6.64%
	Internet usage	−0.001	−1.01%	−0.005	−4.31%	0.003	2.81%
	Share of agricultural labor	0.002	2.21%	0.004	3.17%	0.001	1.08%
	Annual household income	0.031	27.34%	0.040	36.21%	0.018	16.30%
	Number of interactions	0.003	2.48%	0.002	1.55%	0.003	2.72%
	Neighborhood effects	0.004	3.38%	−0.004	−3.94%	0.013	11.94%
	Planting scale	−0.034	−30.77%	−0.038	−34.08%	−0.046	−41.28%
	Number of land plots	−0.001	−1.04%	0.008	6.85%	−0.006	−5.76%
	Extension services	0.004	3.53%	0.001	0.82%	0.006	5.46%
	Support subsidies	0.000	−0.19%	−0.001	−0.57%	0.000	0.33%
	Total explainable part	0.029	26.11%	0.032	28.40%	0.010	8.77%
Unexplainable part		0.082	73.89%	0.080	71.60%	0.102	91.23%
Total difference		0.112	100%	0.112	100%	0.112	100%

Conclusions

Based on the field research data of mango farmers in Hainan Province, this paper analyzed the differences and sources of differences in CLPB between smallholders and professional farmers using the Logit model and Fairlie decomposition method, and the following conclusions were obtained: Firstly, the mean values of CLPB of smallholders and professional farmers were 0.292 and 0.403, respectively, and were significant at the 5% level, showing the adoption ratio of organic fertilizer and soil testing and fertilizer application by the two types of farmers was relatively low. Secondly, education has a significant positive impact on both smallholders and professional farmers, while planting scale significantly negatively impacts the two types of farmers. Thirdly, there are differences in CLPB between smallholders and professional farmers, including differences in external characteristics based on observable factors such as family socio-economic characteristics and internal characteristics based on unobservable factors such as sense of identity, adaptability, responsibility, and belonging. Fourthly, 73.89% of the reasons for the differences in CLPB between smallholders and professional farmers are due to internal characteristics, while the remaining 26.11% are due to differences in external characteristics, of which planting years, annual household income and planting scale and planting scale contribute most.

Data availability statement

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

Author contributions

TX and HC: conceptualization and formal analysis. HC and DQ: methodology. TX and YJ: software. TX, HC, DQ, and FW: validation and writing—review and editing. TX and DQ: investigation and project administration. DQ and FW: resources and supervision. HC and YJ: data curation. TX, HC, and YJ: writing—original draft preparation. DQ: funding acquisition. 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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Re-assembling land degradation: toward a nature-society-inclusive soil erosion management strategy. A case of the Rwenzori region, Uganda

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Tackling land degradation, particularly soil erosion, remains a challenge due to the gap between science, policy, and practice which hampers the adoption of control measures by farmers. Bridging this gap requires understanding land degradation as an assemblage of the natural/biophysical and anthropogenic aspects; but also, rethinking epistemologies that level the grounds between scientists, policymakers, and farmers whose farm livelihoods are at-risk due to soil erosion. This study aimed to clarify how these requirements can be met through the lens of the recently proposed *hylomorphic framework*. This framework structures, in three steps, the procedure of bridging real-life experiences of farmers at risk of soil erosion with the knowledge of scientists and policymakers through the embracement of diversity in ontological realities and values, self-critiques, and coalescing overlaps in theorizations. We selected a qualitative design as most appropriate using one of the cases—the Rwenzori region—where soil erosion is high. We conducted nine focus group discussions with participants selected purposefully from three stakeholder groups including scientists, policymakers, and farmers. Following the hylomorphic framework procedure, we carried out the content analysis. Drawing on insights from this study, we elaborate on how the hylomorphic framework supports deconstructing land degradation and soil erosion, and also further offers insights into a more nature-society-inclusive soil erosion management strategy.

KEYWORDS

land degradation, land use, natural hazards, soil management, sloping land

1. Introduction

Tackling "soil erosion" continues to be a challenge, especially among smallholder farms in tropical mountain regions where rainfall-induced erosion is high (El-Swaify and Dangler, 2015; Labrière et al., 2015). This is exacerbated by the steeply sloping land in these areas (Shanshan et al., 2018) and the traditional farming methods such as continuous hoeing and burning of plant residues which cause land degradation (Barungi et al., 2013; Eswaran et al., 2019). While this can be attributed to limited appropriate agricultural advisory services in these regions (Pender et al., 2004; Muhamud, 2015), it is also due to the mismatch between scientific as well as policy recommendations and the practices of the farming communities (Andersson et al., 2011; Poesen, 2018; Eswaran et al., 2019; Kelly et al., 2020).

In several related studies (Boardman, 2006; Andersson et al., 2011; Ramisch, 2014), this mismatch is largely attributed to the conceptualization of soil erosion control by scientists as well as policymakers; they largely follow the modern ontology which artificially separates humans from non-humans as well as the political from the technical (Latour, 2004; Collard et al., 2018). Meanwhile, most studies on soil erosion have focused on its aspects of computation, prediction, and measurement with policies that omit local perspectives (Boardman, 2006). Consequently, the epistemologies that derive from such a segregated ontology lead to the know-how of the biophysical or natural reality that is distanced from social or anthropogenic aspects of natural hazards (Bwambale et al., 2020; Mertens, 2021). More specifically, by focusing on the natural elements, scientists adhere to the hazard paradigm, depoliticizing soil erosion control, and thus ignoring the socio-economic aspects through which events like soil erosion occur (Zakour and Swager, 2018). They also, neglect local social learning as well as indigenous knowledge, infringing a systems approach and practices that would enhance tackling soil erosion (Tibasiima et al., 2022). This, according to various studies (Boardman, 2006; Akhtar-Schuster et al., 2011; Wilson et al., 2017; Bwambale et al., 2022b), also limits understanding of how anthropogenic and natural processes interact to cause soil erosion, and hampers the development of holistic strategies to best tackle it (Ashmore, 2015).

Toward solving such multifaceted constraints, various studies currently emphasize holistic approaches which go beyond taking into account the natural (looking into the triggers and controlling factors) and exploring the socioeconomic, cultural, and political contexts in which soil erosion occurs (Pender et al., 2004; Bewket, 2011; Teshome et al., 2014; Ekyaligonza et al., 2022). This aligns with the assemblage perspective which facilitates the re-conceptualizing of an issue to best develop means to tackle it from the hybrid of the social and natural, and the human and non-human aspects. This, itself, is possible when a hybrid epistemology is developed that enables understanding phenomena such as soil erosion as social natures in causing as well as tackling it (cf. Ashmore, 2015). For instance, the capture of the real-life experience through social and economic aspects and also the natural processes (such as triggers) and control their occurrence in which an issue such as soil erosion occurs. This implies that soil erosion control addressing the social and the natural aspects should be observed as "two faces of the same coin." Thus the social is integrated with the natural or non-anthropogenic, and the natural, vice versa, with the social, thereby pointing to a nature-society-inclusive context-specific soil erosion management strategy (Bewket, 2011; Tibasiima et al., 2022).

The management of soil erosion has not just continuously pointed to an understanding of land degradation as an assemblage or hybrid of the natural and anthropogenic aspects, but also, an epistemology that levels the grounds between scientists, policymakers, and farmers whose farm production, as well as livelihoods, are at-risk (Latour, 1993; Boardman, 2006; Ashmore, 2015; Poesen, 2018; Tibasiima et al., 2022; Mertens et al., 2023). The assemblage perspective welcomes different ontological groups, thereby enabling conceptualizing phenomena across multiple disciplines, including natural and social sciences, as well as among farmers, scientists, and policymakers. This would be the basis for a common epistemic understanding among actors, including scientists, policymakers, and farmers that enables the co-creation of knowledge as well as the co-development of context-specific soil erosion management practices that would be practically and sustainably implemented. To date, discrepancies between science, policies, and practice in soil erosion management hinder context-specific solutions. Moreover, soil erosion studies or frameworks toward assemblage thinking and a hybrid epistemology from which to draw context-specific soil erosion control measures are scarce.

As a step toward filling this gap, and based on the case of the Rwenzori region of western Uganda (a soil erosion-prone region), this study applied the recently developed *hylomorphic framework*. This framework was developed in natural hazard or disaster risk studies for bridging the real-life experiences of the communities at risk with the theoretical knowledge of scientists and policymakers (Bwambale et al., 2020; Bwambale and Kervyn, 2021). The motive was to not only enable the co-creation of knowledge but also propose a strategy for the co-development of options for solving natural land degradation-related disasters, particularly soil erosion. The framework presented an un-tested potential for eliminating the separation between elements that are social and natural as well as human and nonhuman. It thus enabled an assemblage in understanding soil erosion and a hybrid epistemology from which to design a context-specific strategy for tackling hazards like soil erosion.

2. Perspectives and theory: the hylomorphic framework in the context of soil erosion

The hylomorphic framework was proposed based on the philosophical theory of hylomorphism from Aristotle's philosophy of nature (Bwambale et al., 2020). It captured the hybrid nature of natural risks by emphasizing the substantial unity of both the real-life experiences of the communities-at-risk, i.e., the *hyle*, and the theoretical perspectives of scientists, i.e., the *morphe*. Thus, it favors a flattened ontology by understanding natural risk from context-specific elements, not only reorienting understanding of these risks as social natures but also facilitating a hybrid epistemology from which to develop strategies for tackling context-specific real-life environmental issues (Bwambale and Kervyn, 2021). By enabling the alignment of science with real-life experiences as well as culture and indigenous knowledge, the hylomorphic framework is a standpoint perspective. Standpoint theorists argue that indigenous knowledge exposes biases in scientific knowledge and integrating it with science enables strong objectivity. Thus, partial overlaps between science and real-life experiential know-how should be merged to enable hybrid know-how and action strategy: *real-life experiential know-how should be vivified to expose their explanatory powers.* Alternatively, related *scientific theorization should be inculturated to find a relevant "receptor" to weave into the local context to facilitate a concrete pragmatic epistemic stance* (Latour, 2004; Ludwig, 2016; Bwambale and Kervyn, 2021; Figure 1).

In the initial testing of the hylomorphic framework, three core processes were observed to facilitate both the flat ontology and hybrid epistemology as well as foster the development of innovative strategies (Bwambale and Kervyn, 2021): *(1) embracement of diversity in ontological realities and values attached to an environmental issue*, a process that levels the ground on what to consider as what constitutes the environmental issue at hand. *(2) self-critiques*, which is a core process since it opens space for equitation socio-political deliberation. Thus, an environmental issue is considered as a social nature as well as a matter of concern as opposed to a matter of fact that would preclude dialogue (Mertens et al., 2023). In other words, geopolitics is here apprehended as a space of free discussions that pave the way to a rational consensus (Mouffe, 2011). This then facilitates the third element, *(3) coalescing overlaps in theorizations of processes,* which enable the constitution of a context-specific knowledge system from which to develop context-specific appropriate measures for managing an environmental issue (Ludwig and El-Hani, 2020).

With these three processes, the hylomorphic framework aligns with the social epistemology tradition which advocates for a pluralistic production of knowledge to tackle issues that confront society. In the specific context of environmental studies, it meets the assemblage perspective, emphasizing nature-society-inclusiveness as well as enabling context-situated knowledge, practices, and innovations (Ashmore, 2015; Ludwig and Boogaard, 2021). We interrogate these processes in this study to understand soil erosion as a social nature, as assemblages of the natural and anthropogenic aspects, and explore if that can enable reaching a rational consensus on the conceptualization, understanding, and development of a context-specific soil erosion control management strategy.

3. Methodology: a case study approach

3.1. The case in the Rwenzori region

The study is based on a case from the Rwenzori region in western Uganda bordering the Democratic Republic of the Congo (Figure 2). The Rwenzori is a relevant case for various socio-ecological reasons. For instance, it is a steep sloping land with high population density, making it one of the areas highly prone to soil erosion in the African tropics (Muhamud, 2015; Karamage et al., 2017). Moreover, it is a region where multiple and frequent natural hazards co-occur (Jacobs et al., 2016, 2019a,b), capable of triggering cascades as well as intense disasters (Wisner and Gaillard, 2009; Shi et al., 2020). Yet, at the same time, there is a mismatch between science and practice in the Rwenzori that contravenes the effective management of hazards to prevent disasters (Maes et al., 2017, 2018; Tibasiima et al., 2022). Furthermore, the Rwenzori is also a region with an established cultural approach and indigenous practices to disaster, which generates resistance to measures imposed by top-down policymakers without consideration for the local context (Bwambale et al., 2018; Tibasiima et al., 2022).

Two additional factors make the Rwenzori relevant to this study. Firstly, it is a region where a recent study highlights the perceived importance of the acceptability of environmental disaster management measures by the local/indigenous people (Maes et al., 2019). Secondly, it is a region in a context of a least-developed economy that has limited resources to implement and sustain highly specialized technologies for soil erosion control (Muhamud, 2015). Hence, the conceptualization of the hylomorphic framework is relevant to identifying what determines the design and consensus-building about the context-specific soil erosion control options. Besides, like in other eroded sloping areas dominated by smallholder *Coffea arabica* farmers, the adoption of soil erosion control in the Rwenzori mountains is low (Muhamud, 2015). In this area, *C. arabica* is grown on soil erosion-prone land at high altitudes suitable for its growth. Thus, soil erosion is a challenge to the sustainability of *C. arabica* production in this area given that climate change is foreseen to push the *C. arabica* production zones to even higher altitudes where soil erosion is more rampant (Ovalle-Rivera et al., 2015). In addition, in this area, *C. arabica* was introduced without implementing erosion control measures thus, their integration into the existing coffee fields is complex and requires hybrid context-specific soil erosion control measures which are currently missing (Tibasiima et al., 2022).

3.2. Data collection

The data collection approaches used were adapted from Bwambale and Kervyn (2021), a study in which the scientific testing of the hylomorphic framework was first conducted. In our study, the point of departure was an in-depth investigation of the existing indigenous and scientific knowledge in the area or communities studied. This investigation followed the themes around which questions were structured to aid data collection, including the local perspectives on soil erosion, the local understanding of soil erosion challenges, and the co-creation of soil erosion control measures. Following these themes, data were collected from three stakeholder groups (Table 2). Participants representing these groups were gathered from the various soil erosion-prone areas of the Kasese district in the southwestern part of the Rwenzori region (Figure 2); but also, from the local university, Mountains of the Moon for some of the soil scientists. Since the study required participants from different stakeholder groups that have knowledge and experience in soil erosion control, purposive sampling was used to identify representatives of different categories (Creswell, 2014).

Focus Group Discussions (FGDs) were the main data collection method, supplemented with reviews of the local archives, related scholarly articles, and policy documents to begin with. We chose FGDs for their acknowledged contribution to policy analysis where stakeholders are enabled to participate in discussions, revealing the underlying power relations (Kahan, 2001). Moreover, they

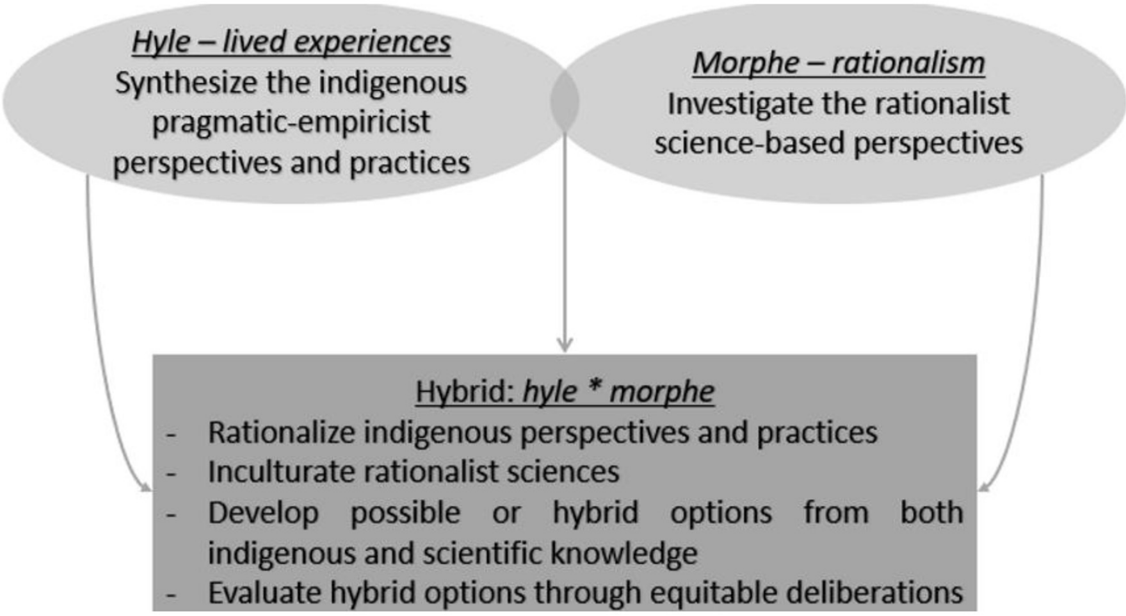

FIGURE 1
Graphical summary of the hylomorphic framework—Adapted from Bwambale and Kervyn (2021).

enhance gathering in-depth data in a participatory manner about disasters (Mercer et al., 2008; Reichel and Frömming, 2014) as well as related analysis in the study area (Maes et al., 2017, 2018). All participants involved in the FGDs were mature adults. The conduct of FGDs followed the procedure elaborated in Hopkins (2007) and Guest et al. (2017), with each FGD having 6 to 12 participants. Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this study. All FGDs were held at the sub-county offices in each sub-county and were conducted in such a way that the themes of discussion were the same across different stakeholder groups (Table 1). The FGDs were conducted in the local language (Lhukonzo) which is majorly used in the studied area. Each FGD took an average of 3-4 hours in which various participatory methods such as problem tree analysis were used.

The selection of participants aimed at knowledgeable members from each stakeholder group. Yet, still, where possible, the inclusion of both female and male participants was considered. The FGDs were conducted with participants from the same stakeholder group at first and then jointly with the three stakeholder groups. The separate FGDs with each of the stakeholder groups were aimed at gathering their views on all the stakeholder groups to develop a composite inventory of views that formed the basis for the joint FGD, as recommended in Bwambale and Kervyn (2021). A total of nine FGDs were held (Table 2). Other methods incorporated into the FGDs were sketch mapping, and problem and solution tree analysis.

The data collection process was conducted between August and December 2022. The farmers that participated were from the hills in Kasese, at an altitude of 1300-1800 m, and soil erosion-prone agrarian communities of the Rwenzori (Figure 2).

3.3. Data analysis

Data were analyzed following content analysis techniques (Fereday and Muir-Cochrane, 2006). The analysis followed the three hylomorphic processes: (1) embracement of diversity in ontological elements and values attached to soil erosion by the different actors. At this level, we explored whether the general perception was different from the context-specific perception. This aided in a common understanding of what constituted the soil erosion issue. (2) Self-critiques enabled a better understanding of the gaps in the current perceptions, the soil erosion control measures, and the co-creation of contextualized epistemologies around soil erosion and its control measures. (3) Coalescing overlaps in theorizations of processes enabled constituting a context-specific understanding of soil erosion from which to develop hybridized measures for managing soil erosion.

The results of this analysis are presented and discussed following the main themes that were coded from the stakeholder-specific FGDs (1-8) and used during the joint discussions (FGD 9). These include (1) Re-conceptualization of soil erosion where the local context perspectives on soil erosion by the different stakeholders were presented. At this level, the main question addressed was: What is soil erosion in the context of the Rwenzori area? (2) Understanding soil erosion contextual challenges. Here, we focused on soil erosion as a hazard that was increasingly causing agronomic losses, in particular, where it mostly occurred, its causes, and its consequences. (3) Contextualized soil erosion management, where soil erosion control measures that have been used were explored in addition to adjustments and new ways to better control soil erosion. The discussions under each of these themes were contrasted with the three processes of the hylomorphic framework

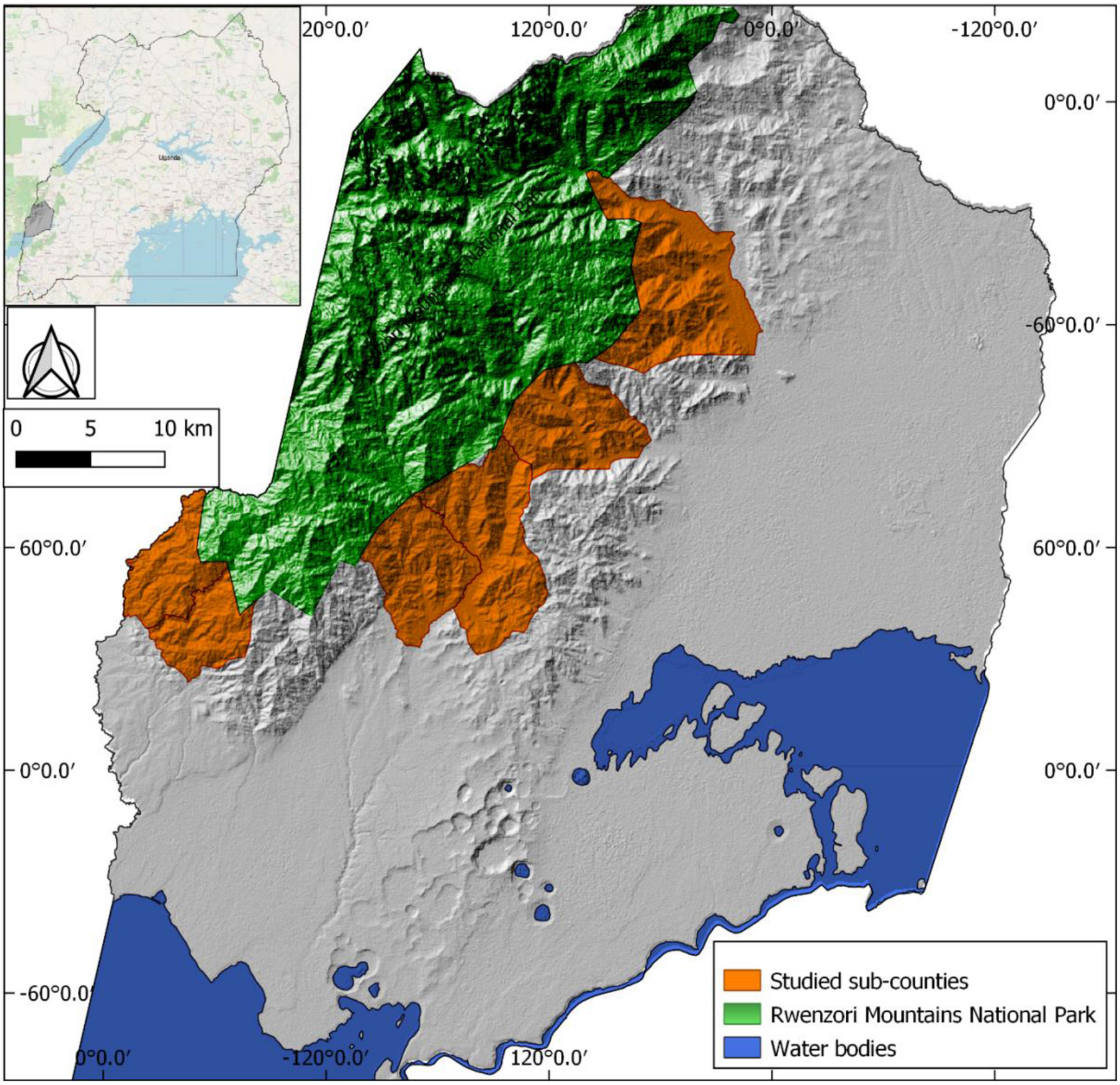

FIGURE 2
The geographical area under study.

as theorized in Section 2 and discussed. The final summing-up is captured in the Conclusions section.

4. Results and discussions

4.1. Re-conceptualization of soil erosion

The hylomorphic framework suggests re-conceptualizing reality from the perspective of social epistemology, enabling a co-production of context-specific knowledge (Bwambale et al., 2020; Bwambale and Kervyn, 2021). At the very outset, some contrasts in the re-conceptualizations of what soil erosion meant in the local context were noticed among the different stakeholders including farmers, scientists, and policymakers. Farmers understood (in consensus) soil erosion in terms of "washing away". This denoted a natural process, implying the ontological natural element of water in the form of rainfall, a key player in soil erosion. They were able to distinguish it from related hazards, e.g., landslides, through the process it takes. This was still in line with the natural sense as is the case in the study areas (Maes et al., 2018). For instance, views extracted from the several FGDs with farmers can be summarized as follows: "soil erosion is the natural wash away of soil, that occurs when it rains on sloping land. It happens over a long time as opposed to landslides which happen instantly" (FGD 1).

On the other hand, for scientists, soil erosion was an anthropogenic process resulting in the loosening of the soil and then such soil being carried away by several agents of soil erosion such as water, wind, and animals. More specifically, in controlling the process, they frequently cited the inability of farmers to implement soil erosion management practices: "soil erosion is the loss of top fertile soil on sloping land that has not been protected from the causes of erosion, and loosened by human activities such as frequent hoeing and overgrazing" (FGD 5). This attribution of soil erosion being a result of human behavior is also commonplace in literature (Nearing et al., 2017). This could be the reason behind scientists and policymakers disregarding the inclusion of natural (spiritual) forces in soil erosion control since they believe that soil erosion is caused by farmers. However, soil erosion is known not only to be human-caused but the causes are understood to be rather complex and geomorphological which result in a land degradation process that may cause environmental and property damage, loss of livelihoods and services, and social and economic disruption (Poesen, 2018). Although there has been no scientisation of the influence of natural forces (spiritual) on the soil erosion process, such broad descriptions of soil erosion could be the foundation for involving an unmeasurable/non-visible (spiritual) aspect in the causation of soil erosion which the farmers term as the "cleansing of the ridges" (Bwambale et al., 2023). It is these discrepancies in the ontological perspectives that prevent the adoption of some of the soil erosion control measures. For example, the fact that farmers call soil erosion a "wash away", implies that they perceive that soil erosion can never happen without rainfall on sloping land. Therefore, they would only adopt measures that control the soil erosion that is caused by rainfall, and whatever is displaced by other agents such as wind, animals, and hoeing are left unchecked. Whereas scientists perceive soil erosion as human-induced, farmers consider it a natural phenomenon that is beyond human control. This discrepancy in the understanding of causation has resulted in scientists perceiving the farmers as mindless keepers of the earth while the farmers consider soil erosion as the fate of their land which due to steep terrain will always be washed away regardless of measures adopted to address it. Farmers, therefore, undertake bare minimal measures to "save just some enough soil" to produce something to survive on. This concept of tolerable soil loss (Isabirye et al., 2007; Hancock et al., 2015; Nearing et al., 2017) explains why farmers let soil erosion continue since it is perceived as a natural process.

TABLE 1 Details about the data collection.

FGD #	Data needed/extracted	Method
1. Farmers at risk	Indigenous, experiences, perspectives, and practices	3 FGDs, local archive reviews
2. Scientists	State-of-the-art scientific soil erosion control measures and any other Scientific recommendations	2 FGDs, scientific article reviews
3. Policymakers	Policy perspectives, recommendations, and implementation	3 FGDs, policy document reviews
4. Joint	Joint dialogue on soil erosion and soil erosion control	1 FGD

A related re-conceptualization was found among the policymakers, concurring that "soil erosion is the destruction of land due to loss of topsoil resulting into loss of livelihoods and famine accompanied by other disasters such as landslides and floods" (FGD 7). Whereas scientists and policymakers perceive soil erosion in terms of loss due to the inability of farmers to implement control measures, the farmers consider the long time it takes to happen and thus connect it to natural causes and less of a loss. Confirming the inference in Section 2 (Hermans et al., 2022), a co-learning attempt was observed among the three categories of stakeholders whenever they acknowledged a new ontological element from each other. For instance, the farmers learned from the scientists and policymakers that in the local context, soil erosion occurred even when there was no rain, implying that it was not just a natural occurrence that was understood as a "wash away"; but it also included any displacement of the soil through human activities such as tillage on a sloping piece of land. For instance, one farmer said,

> "...when we cultivate on sloping land, we displace the soil and thus create erosion in the absence of being washed away. We have also made the land easy to be carried away by constructing big iron-roofed houses. Therefore, soil erosion is not only caused by uncontrollable natural forces. It is not a wash-away but a displacement of soil" (FGD 9).

As theorized in Section 2, these overlaps enabled a hybrid understanding of soil erosion in the local context. Specifically, through the embracement of diversity in ontological realities as

TABLE 2 Details of FGDs conducted.

FGDs	Stakeholder group	Selection criteria	Participants per FGD
FGDs 1-3	Farmers at risk	Smallholder (>2 acres) farmers cultivating on eroded sloping land	3 females, 3 males, 2 youths
FGDs 4-5	Scientists	Involvement in advising farmers on soil erosion	2 district councilors, 3 NGOs (KOFLEC, GLOFA, and BETT), 2 academia (MMU)
FGDs 6-8	Policymakers	Responsible for the formulation and implementation of regulatory guidelines on soil erosion	3 females from the district, 2 males from sub-county, 2 females and 2 males from local council 1
FGD 9	Farmers at risk, scientists, and policymakers	Participation in any of FGD 1, 2, or 3	3 farmers, 3 scientists, and 3 policymakers

well as the self-critiques, a hybrid comprehension of soil erosion emerged that soil erosion was both a natural and human-induced displacement of soil occurring on both sloping and flat lands which continued beyond the topsoil unless control measures were put in place. It posed no immediate threat to completely destroy livelihoods since alternative livelihood sources embedded in the social support structures such as food and seed sharing among farmers and emergency saving schemes existed. For a long time, therefore, soil erosion had stayed within tolerable soil loss amounts.

4.2. Contextual challenges of soil erosion

The re-conceptualization in the preceding section paved way for the participants to have a fresh dialogue on soil erosion, a hazard that increasingly caused agronomic losses. In the past, participants indicated, soil erosion was not explicitly identified as a challenge. Therefore, we aimed to find out how and when it gradually emerged as an issue. Towards this end, we explored key questions such as: what changes have occurred in the ontological setup of the triggers, susceptibility, driving factors, exposures, and vulnerabilities? What was the understanding of the stakeholders on how these changes have facilitated soil erosion as a challenge for farming communities?

According to the farmers, the sloping hills were previously (in the 1960s) reserved as "holy places" and designated for purposes other than farming and settlement:

> Such places were never to be tampered with. Now, these hills have been cultivated or built up and when the soil from these hills is being washed away, it takes along the soil from the gardens. But currently, even when there is no runoff from the holy hills, if you have constructed a big iron-roofed house, the land will be eroded. There are times when it is severe and the whole land mass is carried away at once. In such a situation, there is no production on our land, then it becomes hard to survive and alternative sources of food have to be sought (FGD 2).

The farmers believed that adopting modern techniques changed their lifestyles and the land was displeased with them:

> We had bushes on the hilltops as the source of grass for thatching houses, with the modernizing of houses by replacing rooftops with iron sheets, the hilltops were cleared. Then came the modern earth-moving machines that were brought to open the roads in the mountains. They caused vibrations and made steep road cliffs that have increased erosion. Also, when you see the gardens near the road, the erosion is more in such fields than in those fields that are not along the roads. Generally, soil erosion is a retaliation of nature against our modernization (FGD 1).

The farmers also felt that they lacked the capacity to control the erosion. They said, "this challenge is beyond our control, but we shall always survive on this mountain" (FGD 3). The farmers also considered the impact of soil erosion as a self-perpetuating curse. From the farmers' perspective:

> soil erosion starts by reducing the food and income of the household, once you are weakened by that, and you are not able to work further on the land. You leave the woman and children to cultivate the land as you (the man) go to find a job on which to derive daily survival. Consequently, conflicts begin in the home then the erosion digs deeper (FGD1).

According to scientists, soil erosion was pronounced in over-cultivated fields. They pointed out, "when you look in the old coffee fields, most of the roots of the coffee trees have been exposed by the erosion" (FGD4). In addition, scientists perceived that farmers had a choice to either control the erosion or let it happen on their farms. They believed that all the farms needed to adopt measures against erosion protecting the entire hill; otherwise, widespread erosion would still overpower the efforts undertaken to address erosion in a single farm. The scientists indicated that:

> soil erosion is not difficult to deal with. If the farmers on a particular hill would all choose to prevent erosion on their fields, then the entire landscape would be protected but because they are not educated, they (farmers) misinterpret the causes and just ignore the erosion (FGD 5).

The scientists felt that the farmers neglected the erosion problem because the farmers believed that they will still survive on the depleted land: "you see the farmers survive on the minimum from the eroded land and that is why they have not taken it seriously" (FGD 4).

According to policymakers, soil erosion was widespread across the region affecting livelihoods and the entire social and economic system, and costing a lot to the government. They said, "The roads on these hills have always been eroded due to the low adoption of soil erosion control on the individual farms. From the bottom of the mountain to the top, the government must spend a lot of money every year to fix roads" (FGD 7). The policymakers also flagged mysterious forces that caused soil erosion in the local context:

> In our local situation, some of the things that are known to control erosion have not worked. We do not know why, but we realize that even where there are big trees near the roads for example such parts are badly damaged during the rain, so we fail to understand how to solve the problem (FGD 8).

With soil erosion continuing to destroy livelihoods despite various measures that have been tried, people have migrated from the mountains resulting in over-crowding of the lowlands below and increasing the pressure on resources in nearby urban areas. In the local context, the challenge of soil erosion was widespread and was understood to be a problem of the entire landscape that endangers the social, environmental, and economic aspects of society. As such it perpetuated itself cyclically and created situations that made its control complex e.g., it started from the hilltops, swept through the entire landscape, reduced crop yield, and caused food insecurity that led to domestic violence which in turn discouraged some family members from participating in soil erosion control measures. The uncontrolled runoff from the unmanaged fields accumulated and eventually destroyed the roads. This consequently hindered the transportation of produce to the market and farmers had to spend more to deliver their products to the market and as a result, received less in return. Farmers, therefore, had to resort to providing manual labor in nearby towns to sustain their day-to-day livelihoods as soil erosion further destroyed the land and rendered it fallow.

Farmers perceived soil erosion as a natural hazard where nature (the spirits of the land) punished human beings, and human beings cannot control such retaliation except by being obedient. On the contrary, scientists and policymakers believed that farmers were responsible for soil erosion because they were not educated and hence insisted that it is by penalizing (charging a huge sum of money) non-adopters that soil erosion can be controlled. However, education does not necessarily contribute to soil erosion control (Pender et al., 2004). Farmers, scientists, and policymakers critiqued their original perception of what caused erosion and where it happened most. For example, the scientists and policymakers highlighted that the Kilembe mines management had also preserved some hill slopes in the 1940s and that was not necessarily done to respect the spirits of the land but rather to protect the land from being weakened by human activity.

> The Kilembe mines management had left the entire area after the road barrier in its natural state thus it is logical that such civilized management could find sense in preserving hills and not for fear of the spirits but the cleansing of the ridges would not be a bad thing to them. After all, this (cleansing of the ridges) does not only entail appeasing the spirits of the land but instead is a cocktail of practices where the land is blessed alongside other activities such as planting cultural trees, planting cover crops, preserving natural covers (*omwepu*) that have been blessed, etc (Bwambale et al., 2022a,b) and hence make the soils strong from being displaced (FGD 9).

This scientisation of the holy hills made it possible for some of the traditional beliefs to be recast in science regarding the causes soil of erosion. Similarly, the farmers understood their contribution in weakening the land and thus, in real practice, through the cleansing of the ridges, could be at the forefront of implementing a combination of different soil-conservation practices to overcome the erosion hazard while contributing to the ecological, social, and economic resilience of the community against soil erosion. However, traditional practices of controlling soil erosion are also known to have their constraints (Ellis-Jones and Tengberg, 2000). The farmers also realized that believing in the spirits as the rebellious forces of nature could be the root cause for them doing nothing about the erosion and consequently accepting to survive on the minimum yields from the eroded land. This had been their logic: "soil erosion will always go on, but the land will never become completely unproductive. Therefore, it should not be treated as a crisis" FGD 1. This perspective of the farmers appeared to agree with the concept of tolerable soil loss that has commonly been referred to in several studies on soil loss and was therefore not unique to the farmers in this study (Isabirye et al., 2007; Hancock et al., 2015; Nearing et al., 2017). However, the concept of tolerable soil loss was challenged in the discussions: "we never neglect a neighbor who takes away an inch of our land, so how can we start agreeing with tolerable soil loss through erosion?" (FGD 9). The stakeholders jointly agreed that soil erosion was a slow hazard that destroyed the ecological, environmental, and social functioning of the entire community. This was opposed to the previous understanding of soil erosion as only an ecological challenge of sloping land. Thus, an appreciation evolved among all stakeholders that soil erosion control called for changes in field practices as well as attitudinal and social change that facilitate the adoption of holistic approaches that have been proposed by several scholars (Bewket, 2011; Teshome et al., 2014; Cordingley et al., 2015; Mwangi and Kariuki, 2015; Tibasiima et al., 2022).

4.3. Contextualized soil erosion management

According to the hylomorphic framework, different ontologies and self-critiques can prepare the ground for hybrid epistemologies. This results in the creation of new knowledge based on the scientization of real-life experiences and the inculturation of theoretical scientific perspectives (Section 2). Currently, there are several methods for controlling erosion but very limited implementation happens (Muhamud, 2015) because measures such as terraces are not contextualized in the local traditions (cf. Bwambale et al., 2022a). For instance, according to the farmers, "We have tried several methods to control soil erosion but still the fields are being eroded amidst even what the scientists have recommended to us such as water trenches. We cultivate our land and leave the fields rough. We believe such rough fields would resist erosion, but it does not". Farmers mainly blame the abandonment of good traditional practices and the introduction of destructive modern technologies for the continuing erosion: "The traditional practices to appease nature have been abandoned but these were ensuring that the spirits protect the land from being eroded. We now construct big homes and roads, and these undermine every effort toward managing erosion. The advice we receive is just we should do modern things in our fields, but they have not been tried by anyone and we know well the consequences that may result from that, so we do not follow blindly (FGD 2)". Findings from other research also suggest that neither farmers nor scientists are doing the correct thing (Ramisch, 2014). However, in the context of the hylomorphic framework, the current soil erosion control measures lack a fit with the local context, and relevant indigenous practices have not been integrated into practice.

The scientists believe that their existing knowledge of soil erosion control is adequate to stop erosion if the farmers do what they have been told. In FGD 4 it was mentioned that:

> Any single known soil erosion control measure particularly the structural measures if well implemented can stop the erosion. However, we have trained the farmers many times, but the adoption does not take place. We do not understand why farmers do not implement practices such as contour bands, cultivating across the slope, terracing, water-catching trenches, cover crops, stone bands, and others whose benefits are well known. It is thus not necessary to find new measures but rather tools to ensure the known measures are implemented (FGD 5).

The policymakers share the same perspective as the scientists. They agree that "the soil erosion control measures are there, and they are many and well known. We have been sensitizing the farmers about several methods, but they do not practice them. The solution will be to punish those farmers that do not do what we tell them otherwise soil erosion is being taken for granted yet it is a big and costly challenge" (FGD 7).

The beliefs on soil erosion and its control held by the different stakeholders were challenged in several ways when different views were critiqued at the joint discussions which included all stakeholders. For example, the belief that a single soil erosion control measure could stop erosion was challenged noting that the slope of the land was too steep for one single method to be effective. The farmers and scientists knew well that water trenches had been tried and it never worked. Even the traditional cleansing of the ridges which was no longer being performed had never worked as a single soil erosion control measure. In reality, studies indicate that the Rwenzori region is still prone to soil erosion (Jacobs et al., 2017; Karamage et al., 2017). The stakeholders, therefore, jointly agreed that contextualized erosion control measures were relevant, but were currently missing. According to them:

> To manage soil erosion is surely not a matter of appeasing spirits and then waiting for them (spirits) to do the work. Neither is it to dig the trenches and the erosion stops, it requires serious innovation where different options that encourage adoption will be integrated into the control measures. It is not about science nor religion separated but reconstructing a strategy that can combine both without undermining the other. We should for example seriously ask ourselves, what and how the cleansing of ridges contributed to soil erosion control so that we adopt the good practice and merge that with the science otherwise no clear negative consequences, for example, justify the abandonment of the cleansing of ridges. It seems it was only misinterpreted to be against religion and science (FGD 9).

Equally, scientifically recommended measures were challenged: "We have seen situations where trenches without stabilizers were broken by runoff and caused more disaster than in the fields where they were never constructed as long as they are implemented near an iron-roofed house that collects a lot of runoffs" (FGD 5). Similarly, several control measures have been criticized and farmer preferences have been given priority (Teshome et al., 2014; Muhamud, 2015; Tibasiima et al., 2022). Policymakers were also equally criticized, although there was a strong belief that if policy regulations were implemented, then erosion would be controlled. It was found that the existing regulations were not clear to the policymakers to implement and create an environment that would enable/ensure the adoption of soil erosion control measures. A critique on policy (from FGD 9) was: "there is no way we can currently use policies to address the challenge of soil erosion. It is not clear and is very broad. We need something rather specific that is familiar and clear to the local situation. Something that is practical and can easily be implemented. But in the current state, no penalties are documented and non is in line with the culture of the local people, currently, no policy regulation fits the local situation." Indeed, the laws related to land use regulations in Uganda are scattered in several pieces of environmental legislation and non-specific (Karamage et al., 2017). This explains why despite several policies on control, soil erosion still exists (Akhtar-Schuster et al., 2011).

Although one local leader indicated that they had a by-law for soil erosion control, efforts to access this document were unsuccessful as the document could have been misplaced and was not known to any other members of the community. In addition, the lack of specific regulations on soil erosion control was also cited in the discussions (Karamage et al., 2017).

In the coalescing of perspectives, we noted that the common thread among all stakeholders about soil erosion management was: "When we speak about this problem of soil erosion, we need to consider that our hills are naturally prone to erosion. Such land should not be continuously tilled. The land use needs to be changed for example to perennial crops with perennial cover crops that have a self-sowing system." Such a cropping system has been recommended for soil fertility management in a study by Ekyaligonza et al. (2022) in the same geographical region. Apart from working on the methods, efforts are also needed on the social and regulatory elements. This will change the attitude of all stakeholders toward the ideologies of one another and soil erosion management will be achieved. The stakeholders reached a consensus that soil erosion cannot be controlled but only managed. For instance, while soil erosion control would imply putting in place structural measures that would interfere with the erosion during its occurrence, management entailed practices to prevent the erosion before it happens. This was the basis for proposing a new soil erosion management strategy. As proposed below, the hybridized soil erosion management strategy that resulted from a cocreated epistemology on the technical, natural, and social aspects addressed soil erosion management at different levels as indicated in Table 3.

5. Conclusion

The three processes of the hylomorphic framework i.e., conceptualization, self-critique, and coalescing overlaps proved insightful in bridging the mismatch between science, policy, and practice, toward co-creating a context-specific soil erosion management strategy. Moreover, the three processes through which the co-creating of knowledge happened leveled the ground and thus facilitated the exposition of blind spots in the re-conceptualization, understanding of challenges, and development of measures to control soil erosion in the current context.

In the re-conceptualization, for example, it was generally taken for granted that soil erosion is a "wash away" of topsoil; yet this study exposed the fact that soil erosion, or rather any form of displacement of soil particles, can be caused by human activity and natural agents. The hybrid understanding of soil erosion as a contextual challenge moved away from the limited understanding of soil erosion as a challenge to the sloping fields that are cultivated; rather, it came to be understood as a cyclic challenge that offsets the ecological, social, and economic functioning of the entire community by breaking the bonds that act against it. The modernist approach toward development was

TABLE 3 Assemblage of a hybrid soil erosion control strategy.

Aspect	Description
Technical/scientific	• Install gutters to harvest water on every iron roof house if not use grass to thatch houses • Cover all courtyards with vegetation cover to avoid the accumulation of runoff • Construct water trenches along the contour at an interval not more than 10 m apart • Stabilize water trenches with strongly rooted vetiver grass on both sides of the trench. Use slashing of weeds instead of hoeing • Replace annual crops with perennial crops and perennial cover crops
Natural	• Traditional cleansing of the ridges (including both the traditional and scientific relevance such as planting of holy plants that are believed to appease the spirits of the land)
Social regulation	• Farmers to work in groups (between 10 and 15 households) implement soil erosion management strategy as opposed to individual households
Bylaw	• Iron-roofed house construction is restricted to households headed by 30 years and above of age either live in their traditional house or on grass thatched roof
	• Any iron-roofed house should have an approved plan which includes rainwater harvesting and a runoff-catching courtyard (with vegetation cover)
	• Avoid hard surfaces that were not in the tradition such as hard surface graves. Instead, traditionally burry in the bark of the *Ficus natalensis* (*Omutoma*) trees
	• 10-15 households that work together should take the non-adopters to authorities
	• Traditional penalties (such as the seven goats) payable by non-adopters instead of cash penalties

also criticized in this context to be facilitating soil erosion through the construction of large iron-roofed houses as a serious example. What was learned in this case was that soil erosion should be dealt with from multiple fronts including social, economic, and field-based interventions.

The re-conceptualization as well as the hybrid understanding of factors that facilitated extremities in soil erosion inspired the co-creation of new soil erosion control strategies. For instance, as opposed to focusing on implementing structural measures and penalizing those who do not adopt soil erosion control, the hybrid contextualized strategy refocused on the *management* of soil erosion rather than *controlling* it. In the hybridized soil erosion control strategy, the management of soil erosion included off-field interventions such as regulating the construction of large iron roofed houses, re-considering the cleansing of the ridges as an integrated package of both traditional and scientific erosion management strategies alongside traditionally recognized regulations such as the payment of seven goats by any household that does not implement soil erosion management. This study found that such a soil erosion management strategy does not exist in any current soil erosion management-related strategies and provides new perspectives toward nature-society-inclusive soil erosion management strategy. The steps suggested in the hylomorphic framework as reflected in the preceding sections have highlighted their relevance in the contextualization of soil erosion management.

Data availability statement

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

Ethics statement

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

Author contributions

TT: conceptualization, investigation, methodology, formal analysis, writing—original draft, and review and editing. BB: conceptualization, investigation, methodology, writing—visualization, review and editing, and mentorship. DE, PD, and FJ: conceptualization and writing—review and editing. JK: conceptualization, methodology, and writing—review and editing. BF: conceptualization, methodology, writing—review and editing, and supervision. 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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