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Enhancing maize (*Zea mays*) productivity through integrated soil fertility management: a participatory approach in the degraded soils of Kigoma, Tanzania

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Maize is a staple cereal for countries in sub-Saharan Africa, characterized by a low average yield of less than 1 ton per hectare in many smallholder farms across these countries. The low maize yield is attributed to poor soil fertility, poor crop management practices, poor post-harvest handling techniques, and erratic rainfall. The objective of the study was to investigate the effects of selected integrated soil fertility management (ISFM) technologies on soil chemical properties and maize yields following the use of the InPaC-S (Portuguese for Integração Participativa de Conhecimentos sobre Indicadores de Qualidade do Solo or Participatory Knowledge Integration on Indicators of Soil Quality) methodological approach. This methodological approach was employed to mobilize farmers through workshops and field experiments using selected integrated soil fertility management options: use of organic manure, lime, and nitrogen, phosphorus, and potassium (NPK) fertilizer. The experiment was laid out in a randomized complete block design (RCBD) with three replications, including manure, lime, NPK, lime + manure, manure + NPK, lime + NPK, and control. The results revealed significant differences between the treatments (p<0.001) and sites (p<0.001) for all studied growth parameters. The use of lime + NPK significantly increased maize yields by 149% (p<0.001) compared to the control and influenced electrical conductivity, cation exchange capacity (CEC), organic carbon, total nitrogen, total phosphorus, and exchangeable bases. In turn, the cost of maize production (USD/ha) varied between treatments, ranging from 419.8 to 630.9 USD in the control and lime + NPK, respectively. The major costs included inorganic fertilizers, weeding, and land preparation, with inorganic fertilizers contributing the most to the total production cost. The net revenue in USD/hectare for the treatments was significantly (p<0.001) highest for lime + NPK ($1,260.90) and lowest for the control ($339.60). A sensitivity analysis was performed on the net income, and the results suggest that as fertilizer costs increase, there comes a point where their use is no longer economically viable. Consequently, different ISFM options, such as the combination of lime and manure, lime alone, and manure alone, become relevant. This empirical evidence concludes that the use of other integrated soil fertility management options will translate to a long-term improvement in food security and better livelihoods among communities. Future research should focus on scaling up/out these ISFM practices to further improve soil health, increase crop yields, and promote better livelihoods in sub-Saharan Africa.

KEYWORDS

maize production, smallholder farming, InPaC-S methodology, soil health, economic viability

1 Introduction

Maize is a major staple cereal for sub-Saharan Africa (SSA), serving as a primary crop for millions of smallholder farms. Despite its importance, maize productivity in SSA, including Tanzania, remains remarkably low, often yielding less than one ton per hectare, far below the potential yield of 4.0–4.5 tons per hectare (Wickama, 2017). The yield gap is attributed to a range of constraints, including poor soil fertility, soil acidity, and loss of soil biodiversity. These constraints are further exacerbated by the limited adoption of improved agricultural practices and technologies (Mesele et al., 2025; Silva et al., 2023; Zingore, 2023; Muindi et al., 2016).

These soil-related challenges are acute in regions like Kigoma, where intensive continuous cultivation on small landholdings, typically ranging from 1 to 2 hectares, results in nutrient depletion and soil degradation over time (Yaseen et al., 2024). Additionally, the inability of farmers to invest in inorganic fertilizers further amplifies this problem, creating a vicious cycle of soil degradation and low productivity (Wato et al., 2024; Wickama, 2017). The major concern is soil acidity, one of the primary factors hindering maize production in Kigoma (Farooqi et al., 2024). Furthermore, the extensive use of acidifying fertilizers such as diammonium phosphate (DAP) without adequate soil amendments only exacerbates this acidity problem (Shanka, 2020). As a result, the degradation of soil, coupled with low input agricultural practices, leads to reduced crop yields, endangering food security for smallholder farmers who rely on maize as their main source of income and nutrition.

In order to address these challenges, this study sought to explore and promote sustainable integrated soil fertility management approaches to restore soil health and enhance maize productivity in the Kigoma region of Tanzania. Specifically, the study aimed to achieve the following objectives: (i) assess the effects of organic and inorganic fertilizers on the chemical properties of the degraded soils of Kigoma region; (ii) evaluate the impact of integrated soil fertility management (ISFM) practices on maize yields in smallholder farms in the Kigoma region; (iii) evaluate the economic outcomes, particularly the net revenue resulting from adoption of ISFM practices [use of manure, lime, nitrogen, phosphorus, and potassium fertilizer (NPK) alone, or in combination] by smallholder farmers of Kigoma region; and (iv) identify effective participatory approaches to engage farmers in integrated soil fertility management research and facilitate the adoption of these practices.

Given the constraints mentioned, there is an urgent need to explore sustainable soil fertility management approaches that can restore soil health and improve maize productivity. One such promising approach is the integration of organic and inorganic fertilizers (Yaseen et al., 2024), a core principle of ISFM. ISFM highlights the efficient and combined use of organic and inorganic resources to address soil fertility issues while enhancing crop production and maintaining long-term soil productivity (Dunjana et al., 2023; Kalibata et al., 2024; Khan, 2024; Mng'ong'o and Ojija, 2024). For example, organic materials such as manure and crop residues, when used alongside inorganic fertilizers such as NPK, have been shown to improve soil organic carbon, enhance microbial activity, and restore soil biodiversity, which are all essential for sustainable agricultural practices (Dunjana et al., 2023; Wamalwa, 2024; Yeboah et al., 2024; Liang et al., 2021; Ayuke et al., 2011). However, despite the proven benefits of ISFM in improving soil fertility and increasing yields, its adoption in regions like Kigoma remains limited. This limitation can be attributed to several factors, including a lack of awareness among farmers about the potential benefits of organic inputs, limited access to quality fertilizers, and inadequate information dissemination strategies (Kiprotich et al., 2024; Yeboah et al., 2024; Pamuk et al., 2014; Mtambanengwe et al., 2012). Furthermore, the majority of the existing research on ISFM has been conducted in experimental settings, with limited farmer involvement in the research process. This resulted in limited practical applications and adoption of the intended technologies (Snapp, 2002; Gwandu et al., 2014). This gap in dissemination and technology adoption highlights the need for more participatory approaches to research that involves farmers in the identification, testing, and implementation of soil fertility management practices.

Moreover, participatory research approaches have been shown to be effective in bridging the gap between research and practical application, as they facilitate the co-learning of farmers and researchers. Studies have demonstrated that when farmers are actively involved in a research process, they are more likely to adopt new technologies and practices (Kuria et al., 2019; Sanginga et al., 2001). An example of such an approach is the InPaC-S (Portuguese for Integração Participativa de Conhecimentos sobre Indicadores de Qualidade do Solo or Participatory Knowledge Integration on Indicators of Soil Quality) methodology, which fosters co-learning between farmers and agricultural scientists to co-develop ISFM options that are both scientifically sound and locally suitable (Barrios et al., 2012). This methodology allows for the identification of "best-bet" options for soil fertility management that are tailored to the specific conditions and needs of smallholder farmers in the Kigoma region.

The integration of the InPaC-S approach in this study aims to address the soil fertility constraints in the Kigoma region through participatory research, identifying and promoting ISFM practices that can enhance soil quality, improve maize yields, and boost the economic sustainability of smallholder farms. This participatory framework distinguishes this study from previous research which often lacked farmer involvement in the research process. Additionally, while the use of combined organic and inorganic inputs has shown promise in improving soil fertility and microbial health, leading to higher yields in other parts of SSA (Iqbal et al., 2021; Liang et al., 2021; Chen et al., 2024; Mahmood et al., 2017), there is still limited information on the specific impact of these practices on soil chemical properties, maize production, and net revenue in degraded soils typical of Kigoma.

Therefore, this study seeks to bridge these knowledge gaps by assessing the effects of integrated organic and inorganic fertilizers on soil chemical properties and ISFM practices on maize yields and net revenue in the degraded soils of Kigoma. By exploring the role of ISFM in restoring soil fertility and increasing maize productivity, the study will contribute to sustainable agricultural practices and provide actionable recommendations for farmers, policymakers, extension services, and agricultural researchers. Thus, the results will offer important insights into promoting more widespread adoption of ISFM through participatory approaches in regions facing similar challenges.

2 Materials and methods

2.1 Location of the study area

The study was conducted in the Kigoma District, located in the Kigoma region in the western part of Tanzania. The region is situated along the shores of Lake Tanganyika (Figure 1) between the latitudes 3.6° and 6.5° south and longitudes 29.5° and 30.5° east (The Planning Commission Dar es Salaam and Regional Commissioner's Office Kigoma, 2016).

The Kigoma District experiences a tropical climate characterized by a unimodal rainfall pattern from late October to

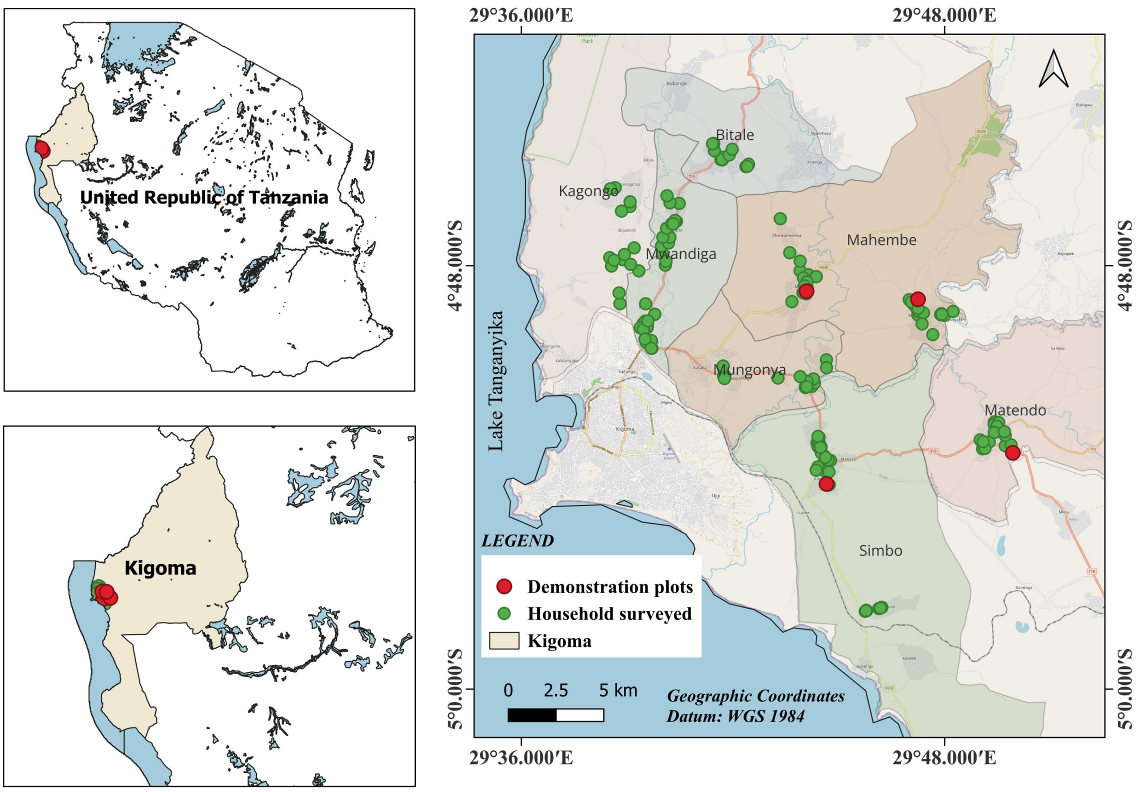

FIGURE 1
A map of Tanzania showing the study area.

May. The mean annual rainfall ranges from 600 mm to 1,500 mm, with an altitude ranging from 750–1,850 meters above sea level. Daily mean temperatures range between 25°C and 28°C, varying with altitude. During the cropping season, the average monthly temperature ranged from 21.7°C to 26.4°C, with the highest temperature recorded in November. The average monthly rainfall ranged from 99.7 mm to 350.8 mm, with the highest rainfall recorded in April and the lowest in January (Table 1).

Soils in the district vary by topography. Along the shores, they are deep, well-drained, and reddish brown fine sandy loams, but severely eroded. In low-lying areas, the soils are black and waterlogged, whereas higher relief areas contain black and brown alluvial soils. Well-drained dark reddish loams dominate other low-relief zones (The Planning Commision Dar es Salaam and Regional Commissioner's Office Kigoma, 2016; Mlingano Agricultural Research Institute, 2006).

2.2 Site selection

A baseline survey was conducted in 10 villages in the Kigoma District to assess the soil fertility status. Data collected from the field covered production constraints, knowledge of ISFM, land tenure system, crop productivity, fertilizer uses, soil types, and soil characteristics. The aim of the baseline survey was to assess and select sites with soil fertility constraints for the study. The Open Data Kit (ODK) tool was used for data collection (Ouma et al., 2019) using Android mobile devices. Based on low soil fertility among the 10 villages, four were selected to conduct demonstration trials, including, Kasuku, (latitude 4°54'11.358"S, longitude 29° 44'39.156"E, and altitude 820m), Kidahwe, (latitude 4°53'18.42"S, longitude 29°44'39.156"E, and altitude 820m), Mahembe (latitude 4°48'43.5672"S, longitude 29°44'5.0352"E, and altitude 1012m), and Nkungwe (latitude 4°48'57.276"S, longitude 29°47'14.7048"E, and altitude 930m).

2.3 Selection of ISFM options

The selection of ISFM options was done in collaboration with farmers during workshop meetings that were undertaken simultaneously with the baseline survey in the study area. Farmers selected ISFM technologies/options based on their soil conditions. In this study, different treatments were adopted, including manure, lime, NPK, lime + NPK, manure + NPK, and lime + manure, which represent various approaches to soil fertility management. However, according to the ISFM principles, true integration involves combining at least one of the organic inputs (manure) with inorganic fertilizer (NPK) or soil amendments (lime) to optimize nutrient availability and soil conditions. Therefore, treatments such as manure + NPK and lime + manure are examples of ISFM approaches, as they strategically integrate organic and inorganic amendments to enhance soil fertility, improve nutrient use efficiency, and support sustainable soil health. Therefore, the field experiments were conducted to validate the best-bet options among the soil management practices selected by the participants.

2.4 Field experiment

2.4.1 Soil sampling and analysis for field experiment

Soil sampling in the demonstration sites was conducted prior to planting and at harvest time. Five soil core samples were randomly collected at a depth of 0–20 cm (Anderson and Ingram, 1993; Santos et al., 2017) and thoroughly mixed to constitute a composite sample as described in Motsara and Roy (2008). A composite sample of approximately 1 kilogram from each site was air dried, ground, and allowed to pass through a 2.0 mm mesh. The soil samples were analyzed at the Tanzania Agricultural Research Institute's (TARI) Ukiriguru Center Soil Laboratory for particle size distribution, soil pH, cation exchange capacity (CEC), exchangeable bases (Ca, Mg, K, and Na), organic carbon (OC), total N, and extractable P.

Carbon and nitrogen were analyzed by thermal oxidation using a CN-analyzer [Flash 2000 NC analyzer (ThermoFischer Scientific, Cambridge, UK)]. Soil pH was measured with a soil:water ratio of 1:2.5 using a pH meter (Anderson and Ingram, 1993). CEC was determined using the ammonium acetate method. Furthermore, available P and exchangeable K, Ca, and Mg were extracted using the Mehlich 3 procedure (Mehlich, 1984) and determined by inductively coupled plasma (ICP) atomic emission spectroscopy (Isaac and Johnson, 1998).

TABLE 1 Average monthly rainfall, temperature, relative humidity, and average wind speed during the study period (2019/2020) in the Kigoma District.

Year	Month	Precipitation (mm)	Temperature (°C)	RH (%)	WS (m/s)
2019	November	116.0	26.4	75.45	2.78
	December	158.5	22.8	85.98	2.29
2020	January	99.7	23.2	86.67	2.17
	February	257.6	24.0	89.81	2.31
	March	308.5	23.8	92.80	2.40
	April	350.8	21.7	93.02	2.51

2.4.2 Experimental design and treatments

The treatment selection was done following the InPaC-S methodological approach (Figure 2) of Barrios et al. (2012), where participants discussed the management options identified from the local indicators of soil quality (LISQ) integrated with technical indicators of soil quality (TISQ). LISQ are the visually observable and identifiable soil properties, features, and characteristics that are used for qualitative assessment of the soil quality status in a given area (Barrios et al., 2006, 2012; Doran, 2002; Doran and Zeiss, 2000). Once the LISQ and TISQ are integrated, they lead to the co-production of hybrid indicators, which are further categorized into permanent and modifiable soil properties. Modifiable constraints, such as low availability of water and nutrients, low or high pH, bulk density, and low organic matter, can be improved through targeted management practices. A distinction is made between the soil that can be modified in the short, medium, and long term based on the time required to achieve a significant reduction in the constraint identified. The methodological guide considers the time the constraints need to be modified in terms of years as follows: short term = less than 2 years; medium term = 2–6 years; and long term = more than 6 years. The distinction between the short, medium, and long term is necessary to facilitate the prioritization of management strategies that will be possible based on the farmer's capacity to use inputs. The ISFM options were then generated and captured in the management options matrix tool (MOMT), which guided the tailoring of ISFM options to soil quality classes and farmers' capacity to use inputs. MOMT is the spreadsheet-based decision-making tool designed to apply a set of decision criteria to a variety of alternatives or strategic options (Barrios et al., 2012). The best-bet ISFM options were agreed during the national and sub-national workshops and were implemented in the demonstration plots.

The experiment was laid out in a randomized complete block design (RCBD) with three replications. Each block was comprised of seven plots, each 4.5m x 4.5m, with 1 m between plots and 2 m between blocks. Three seeds per hole were planted with a spacing of 0.75 m × 0.5 m, and, 21 days after emergence, thinning was conducted to retain two plants per hole to maturity. The test crop in the study was maize variety TH 501 bred at TARI Tumbi center, tolerant to maize streak virus, leaf blight, and rust, and suited for areas with an altitude of 0–1,400 meters above sea level (m.a.s.l) and rainfall of above 600 mm in medium to light, fertile, and well-drained soils.

The treatments comprised inorganic fertilizer, manure, and agricultural lime. The fertilizer used for basal application was N=13:P=24:K=12, while urea (46% N) was used as a top dressing. The manure was composted cattle manure with the following nutrient contents: 30% C; 1.5% N; 0.64 ppm of P; 0.8 cmol kg K; 1.4 Cmol kg calcium (Ca). The lime treatment consisted of high calcium limestone ($CaCO3$) with 40% Ca (Table 2). Lime and

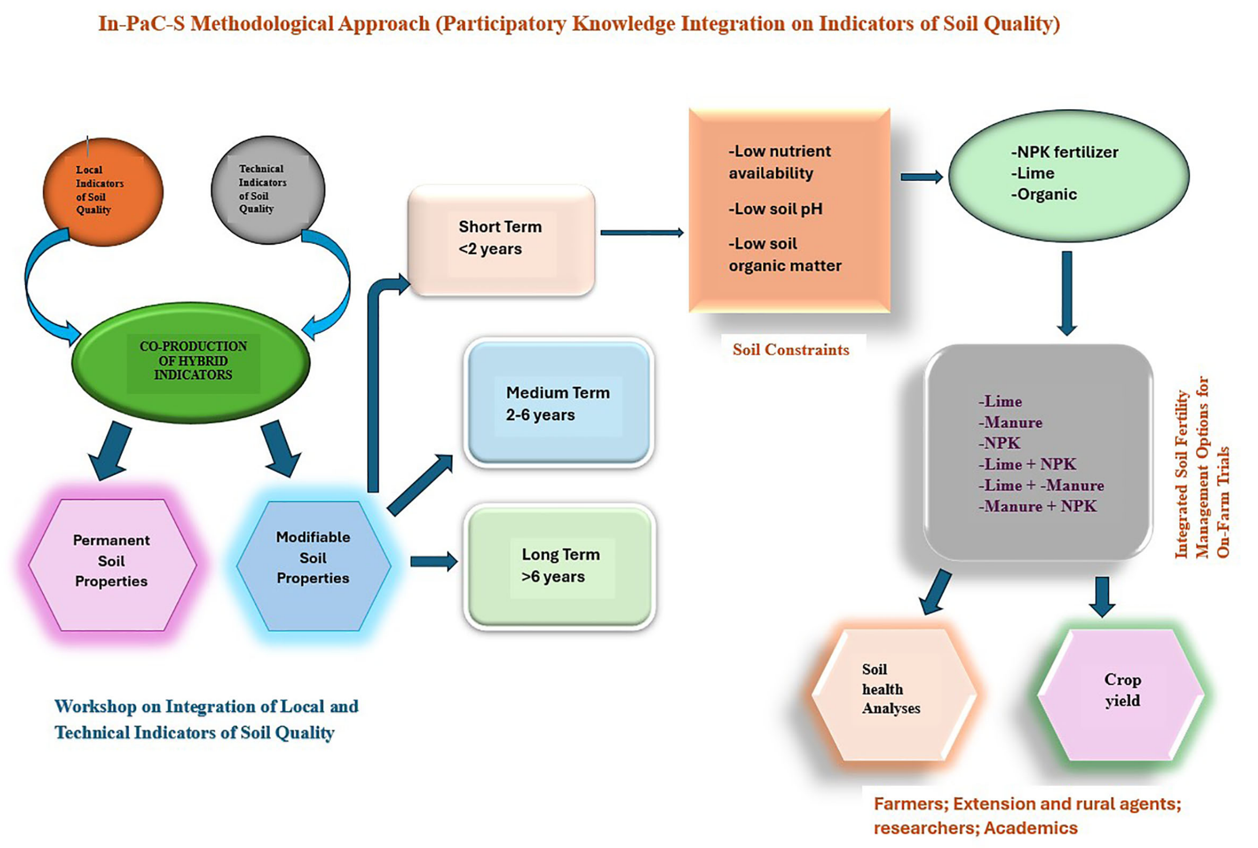

FIGURE 2
A flow chart that illustrates participatory knowledge integration for indicators of soil quality.

TABLE 2 Input treatments at Mahembe, Kidahwe, Nkungwe, and Kasuku sites during the 2019/2020 season.

Treatment	Application rates			
	Manure	Lime	NPK	Urea
Control	No input applied			
Manure	5 tons/ha	–	–	–
Lime (CaCO3)	–	3 tons/ha	–	–
Lime + manure	5 tons/ha	3 tons/ha	–	–
NPK + urea	–	–	104 Kg ha^{-1}	101 Kg ha^{-1}
NPK + urea + manure	5 tons/ha	–	104 Kg ha^{-1}	101 Kg ha^{-1}
Lime + NPK + urea	–	3 tons/ha	104 Kg ha^{-1}	101 Kg ha^{-1}

manure were spread and covered with the topsoil using a hand hoe 3 weeks prior to planting. The starter dose of NPK fertilizer was applied at a rate of 104 kg ha^{-1}, contributing 13.5 kg of N, 25 kg of P, and 12 kg of K ha^{-1}, at planting and placed at a 4 cm depth in each plot, and covered with soil before seed sowing. The second dose of urea was applied at a rate of 101 kg ha^{-1}, contributing 46.5 kg of N, and was done 3 weeks after the first weeding in plots that received NPK. During the growth and developmental stages of the maize plants, management practices, including thinning, weeding, fertilizer application, and disease control, were done accordingly (International Institute of Tropical Agriculture, 1982) (Table 2).

When the maize plants were mature and ready for harvest, plants were sampled from the central rows of each experimental plot at each site, with all edge rows excluded to prevent potential edge effects. Harvesting was done at the physiological maturity using standardized protocols. Plants were manually harvested, and key agronomic parameters, including maize grain yields, below and aboveground biomass, cob length (CL), plant height, thousand seed weight (TSW), and grain weight per plot, were recorded.

2.5 Data collection and analysis

During crop development, the following data were recorded: plant population $plot^{-1}$, plant height, and visual observations. During harvest, 20 maize plants were randomly collected from the central rows in each plot. Maize cobs were extracted, dried, and shelled, and the grains were dried to 12%–15% moisture content. The weight of grain harvested from each plot was determined, and the yield was expressed in tons per hectare (t ha^{-1}). Other yield parameters collected were plant height, CL, TSW, and above- and belowground biomass dry weight. Other socioeconomic data recorded were costs of production that included input and operation costs, and output prices. Tests for normality were performed using the Shapiro–Wilk test in R statistics, and where the data was not normally distributed, square root transformation of the data was done prior to data analysis. Analysis of variance (ANOVA) was performed on the collected variables using GenStat software version 18 (www.genstat.com; VSN International Ltd, Hemel Hempstead, UK). Additionally, Microsoft Excel was used for a cost-benefit analysis, and a sensitivity analysis was conducted. These analyses aimed to establish the realized net returns and their stability across ISFM options.

3 Results

3.1 Initial soil properties

The analysis of the initial soil properties showed that the soil texture of the area was silty loam with moderate water holding capacity (Table 3). Generally, sandy soils have low moisture retention capacity, which is higher for clayey soils (Salter and Williams, 1965).

The soils from the study sites had CECs ranging from 1.74 to 5.20 cmolc (+) kg^{-1} (Table 4). According to Landon (1991), CEC values less than 15 cmol kg^{-1} are considered low. The low values of CEC in this study are directly related to the low organic matter content observed in the soil analysis. Soils with high CEC have a high surface area, which effectively comes into contact with water and soil nutrients. Soares and Alleoni (2008) and Kome et al. (2019) suggested that CEC is largely influenced by soil texture, clay content, and types of clay minerals.

The low values of exchangeable cations Ca (1.71–2.61 cmol kg^{-1}), Mg (0.22–0.58 cmol kg^{-1}), and K (0.03–0.05 cmol kg^{-1}) observed in this study can be attributed to the low CEC values recorded (Table 4). Similarly, according to Lambooy (1984), soils with low CEC will also have low OC (2.03%–2.54%), total nitrogen (TN) (0.11%–0.14%), and available P (10.00–12.30 ppm). The observed low soil nutrient values in all villages were attributed to very low organic carbon contents and low soil pH.

3.2 Effects of treatments on the soil chemical properties

The treatment of lime co-applied with fertilizer (lime + NPK) significantly increased soil pH. In contrast, there was a significant increase in EC, CEC, and exchangeable calcium in soils that received lime co-applied with manure (lime + manure), whilst manure applied alone significantly increased K.

TABLE 3 Initial soil properties (depth of 0–20 cm) prior planting in the four sites, Kigoma.

Soil properties	Site			
	Kasuku	Kidahwe	Mahembe	Nkungwe
pH (H2O)	5.35	4.4	5.07	4.13
OC (%)	2.04	2.08	2.09	2.51
TN (%)	0.13	0.13	0.12	0.12
P (ppm)	11.65	12.35	10	12.05
EC (mS/Dm3)	0.03	0.05	0.03	0.04
K (cmol/kg)	0.03	0.05	0.05	0.03
Ca (cmol/kg)	2.16	2.38	1.82	2.6
Mg (cmol/kg)	0.57	0.46	0.28	0.47
CEC (me/100g)	4.07	4.61	2.5	1.75
Sand (%)	77	58	74	37
Silt (%)	11	25	13	45
Clay (%)	12	15	16	19
Textural class	Silty loam	Silty loam	Silty loam	Loam

OC, Organic Carbon; TN, Total Nitrogen; P, Phosphorus, EC, Electrical Conductivity; K, Potassium; Ca, Calcium; Mg, Magnesium; CEC, Cation Exchange Capacity.

All treatments with lime, whether solely or in combination with NPK or manure, generally increased soil pH when compared to the control. Soil pH significantly differed ($p = 0.009$) among the treatments with lime + NPK, recording the highest pH of 6.51 compared to 4.48 in the control plots. The results also revealed that treatment had significant effects on EC ($p < 0.009$) and CEC ($p < 0.001$), with lime + manure recording the highest EC (0.12 me100g^{-1}) and CEC (9.18 me100g^{-1}) compared to 0.04 and 1.87 me100g^{-1} in the control plots respectively, which translated to 300% and 490% increases, respectively (Table 5). Similarly, the lime + manure treatments had significant effects on exchangeable calcium, recording 5.38 cmol kg^{-1} Ca as compared to 2.12 cmol kg^{-1} in the control plots, which translated to a 326% difference. The sole manure treatment had significant ($p < 0.001$) effects on exchangeable K, recording the highest exchangeable K of 0.1 cmol kg-^{1} compared with 0.03 cmol kg-^{1} in the control plots and this translated to a 233% difference. The results also showed that available P was the lowest in the control compared to other treatments, however, there was no significant difference among the other treatments. NPK + manure recorded the highest phosphorus of 13.43ppm against 9.56ppm in the control, which translates to a 40.5% difference (Table 4; Figure 3).

The results also showed that available P was significantly ($p < 0.002$) lower in the control compared to other treatments. However, NPK + manure recorded the highest phosphorus content of 13.43ppm against 9.56ppm in the control, which translates to a 40.5% difference.

The results showed that total C was significantly ($p < 0.039$) lower in the control compared to the other treatments, but the other treatments did not record significant difference. However, it was noted that lime + manure recorded 28% higher total C compared to the control.

To further gain an insight into the results, a regression analysis was conducted with additional insights into the relationships between ISFM treatments and soil parameters. Both the ANOVA and regression analyses (Tables 4, 6) identified significant effects of ISFM treatments on soil pH and potassium. However, discrepancies between both analyses were observed for OC, calcium, and phosphorus. While ANOVA showed significant treatment effects on calcium and P, these effects were not evident in the regression analysis. In contrast, the regression analysis revealed a significant positive effect of the NPK+manure treatment on TN, a result that was not detected by ANOVA. This shows the role of combined organic and inorganic inputs in enhancing N retention.

3.3 Effects of the treatments on maize growth performance and yields

The analysis of variance results for treatments, sites, their interactions, and the mean effects of the treatments on growth performance and maize yields are presented in Table 7. The results showed a significant difference ($p < 0.01$, $p < 0.001$) for all growth parameters studied except for TSW. This implies that the treatments had a significant contribution to maize growth performance.

The lime + NPK treatment significantly influenced multiple maize growth parameters, including belowground biomass (BgB), grain weight per plot (GWP), plant height (PH), CL, aboveground biomass dry weight (AgB), and overall maize yields. Notably, the lime + NPK, NPK + manure, and NPK had significant effects on GWP, but no significant differences were recorded among the three treatments. However, lime + NPK (12.07 kgs) recorded the highest GWP difference compared to the control (4.82 kgs), with a 150% increase over the control. The increase in GWP compared to the

TABLE 4 Effects of lime, manure, and NPK fertilizers on the soil chemical properties.

Treatment	pH (H20)	EC(Sm^{-1})	CEC (me $100g^{-1}$)	OC (%)	TN (%)	P (ppm)	K(cmol kg^{-1})	Mg(cmol kg^{-1})	Ca(cmol kg^{-1})
Control	4.48[a]	0.04[a]	1.87[a]	1.85[a]	0.12[a]	9.56[a]	0.03[a]	0.32[a]	2.12[a]
Lime	6.26[cd]	0.11[bc]	5.36[bc]	2.27[b]	0.14[a]	13.08[b]	0.08[b]	0.62[b]	4.09[cd]
Manure	5.51[b]	0.07[ab]	4.56[b]	2.30[b]	0.13[a]	11.95[b]	0.10[c]	0.57[b]	3.53[bc]
NPK	5.35[b]	0.08[bc]	4.15[b]	2.20[b]	0.15[a]	12.81[b]	0.08[b]	0.79[b]	2.70[ab]
Lime + Manure	5.60b	0.12[c]	9.18[d]	2.37[b]	0.43[a]	12.19[b]	0.08[b]	0.76[b]	5.38[e]
NPK + Manure	5.84bc	0.07[ab]	4.74[b]	2.26[b]	0.43[a]	13.43[b]	0.08[b]	0.75[b]	3.69[bc]
Lime + NPK	6.51d	0.09[bc]	6.70[c]	2.35[b]	0.15[a]	12.63[b]	0.07[b]	0.72[b]	4.88[de]
CV	3.9	19.6	12.9	5.8	64.3	5.2	1.8	10.6	10.6
LSD	0.55	0.04	1.83	0.31	0.37	1.57	0.02	0.33	0.96
SE	0.18	0.01	0.62	0.11	0.12	0.53	0.01	0.11	0.32
p-value	**0.001**	**0.009**	**0.001**	**0.039**	0.298	**0.002**	**0.001**	0.093	**0.001**

EC, Electical Conductivity; CEC, Cation Exchange Capacity; OC, Organic Carbon; TN, Total Nitrogen; P, Phosphorus; K, Potassium; Mg, Magnesium; Ca, Calcium.
p-values marked in bold are significant: *$p<0.05$; **$p<0.01$; ***$p<0.001$.
Mean followed by the same case lowercase letters are not significantly different at $p<0.05$.

10.3389/fagro.2025.1537292

TABLE 5 Treatments effects on maize net revenue.

Site	Net revenue ($)
Nkungwe	237.60[a]
Kasuku	893.40[b]
Kidahwe	1,023.50[bc]
Mahembe	1,147.70[c]
Treatment	
Control	339.60[a]
Lime	786.10[bc]
NPK	970.30[cd]
Manure	641.50[b]
Lime + Manure	769.00[bc]
NPK + manure	1,011.60[d]
Lime + NPK	1,260.90[e]
***p*-value**	
Treatment	**<0.001**
Site	**<0.001**
Treat × Site	**<0.001**

Values in bold are significant: p<0.001***.
Mean followed by the same case lowercase letters are not significantly different at p<0.05.

control in the different sites was as follows: Kasuku (141%), Kidahwe (103%), Mahembe (102%), and Nkungwe (736%). Similarly, both lime + NPK and NPK + manure recorded significantly higher TSW, but no significant differences were found between the two treatments. Lime + NPK recorded a 54% higher TSW compared to the control. Overall, the treatments and sites had a significant effect on all growth parameters except for TSW, indicating that the applied treatments contributed significantly to enhancing maize growth.

Significant variations in the maize yields and other crop parameters were observed across the four sites. Kidahwe recorded significantly higher BgB and AgB compared to the other sites, while Kasuku recorded significantly higher PH and CL. In contrast, Nkungwe recorded significantly lower yields, whereas the other three sites recorded higher yields, but there was no significant difference among them. However, Mahembe recorded the highest maize yield of 5.2 t ha^{-1}, with grain weight m^{-2} and grain weight $plot^{-1}$ following a similar trend to that of maize yield.

Maize yield showed significant differences (p <0.001) among the treatments, with lime + NPK recording the highest yield of 5.9 t ha^{-1} compared to 2.4 t ha^{-1} in the control, reflecting a 149% increase compared to the control. Lime + NPK consistently outperformed all the other treatments across all sites, recording the highest percentage increase in all parameters. Yield increases over the control across the different sites were as follows: Kasuku (141%), Kidahwe (103%), Mahembe (99%), and Nkungwe (736%). Similarly, the results also revealed that lime + NPK recorded the highest AgB of 4.3 kg compared to 2.1 kg in the control, which represented a 106% increase overall. Site-specific increases compared to the control were as follows: Kasuku (239%), Kidahwe (74%), Mahembe (140%), and Nkungwe (46%). In contrast, there was a significant difference in PH in lime + NPK with 2.65 m compared to 1.66 m in the control plots, resulting in a height increase of 59.21% overall above the control. The different sites recorded increases compared to the control as follows: Kasuku (34%), Kidahwe (84%), Mahembe (55%), and Nkungwe (74%). Furthermore, BgB was significantly higher in lime + NPK, with a 178% increase compared to the control (p < 0.002). The site-specific increases in BgB compared to the control were as follows: Kasuku (646%), Kidahwe (74%), Mahembe (433%), and Nkungwe (62%). Finally, lime + NPK recorded the longest CL compared to the other treatments, which resulted in a 47.6% overall increase in cob length over the control. Site-specific increases in cob length compared to the control were as follows: Kasuku (40%), Kidahwe (41%), Mahembe (39%), and Nkungwe (79%) (Figure 4).

To further explore the relationships between soil and plant growth parameters across different integrated soil fertility management treatments, a correlation analysis was conducted. The results revealed several significant associations that show the factors influencing crop parameters (Figure 5). The correlations observed were consistent with the ANOVA results (Table 6), reinforcing the observed trends and interactions.

3.4 Cost-benefit analysis

Table 8 presents the net revenues that were calculated based on the maize yield from each treatment on a per-hectare basis. The cost of maize production ranged from USD 419.8 in the control to USD 886.70 for the NPK + manure plots. In the trial, the major costs included inorganic fertilizers, weeding, and land preparation. Inorganic fertilizer contributed the highest cost, ranging from 29.5% to 32.5% of the total production cost for plots that received inorganic fertilizers. Similarly, weeding and land preparation costs were high and cut across all the treatments, with weeding costs ranging from 20.0% to 32.7% of the total treatment cost in the inorganic fertilizer + manure and control, respectively, while land preparation costs ranged from 10% to 16.3% of the total treatment cost. Other costs included seeds, planting, pesticides, harvesting, shelling, packaging, and transport, which were generally lower. During the trial, an outbreak of fall armyworms was observed, and pesticide sprays were applied to eradicate them.

The market price of maize per 100 kg bag at the time of harvest was 32 USD (equivalent to TZS 77,965). This was used to determine the net revenue generated from maize production. The net revenue generated was significantly highest for Mahembe at USD 1,147.70 per hectare, while it was lowest for Nkungwe at USD 237.60. Similarly, across treatments, it was significantly highest for lime + NPK (USD 1,260.90) and lowest for control (USD 339.60), all on a per-hectare basis (Table 5).

Figure 6 presents the revenue generated when manure is purchased or not. Removing the cost of manure increases the revenue generated from the manure, lime + manure, and NPK + manure treatments by 64.4 USD ha^{-1}. The use of manure over the long-term by the smallholder farmers will improve soil fertility in their farms and hence their yields.

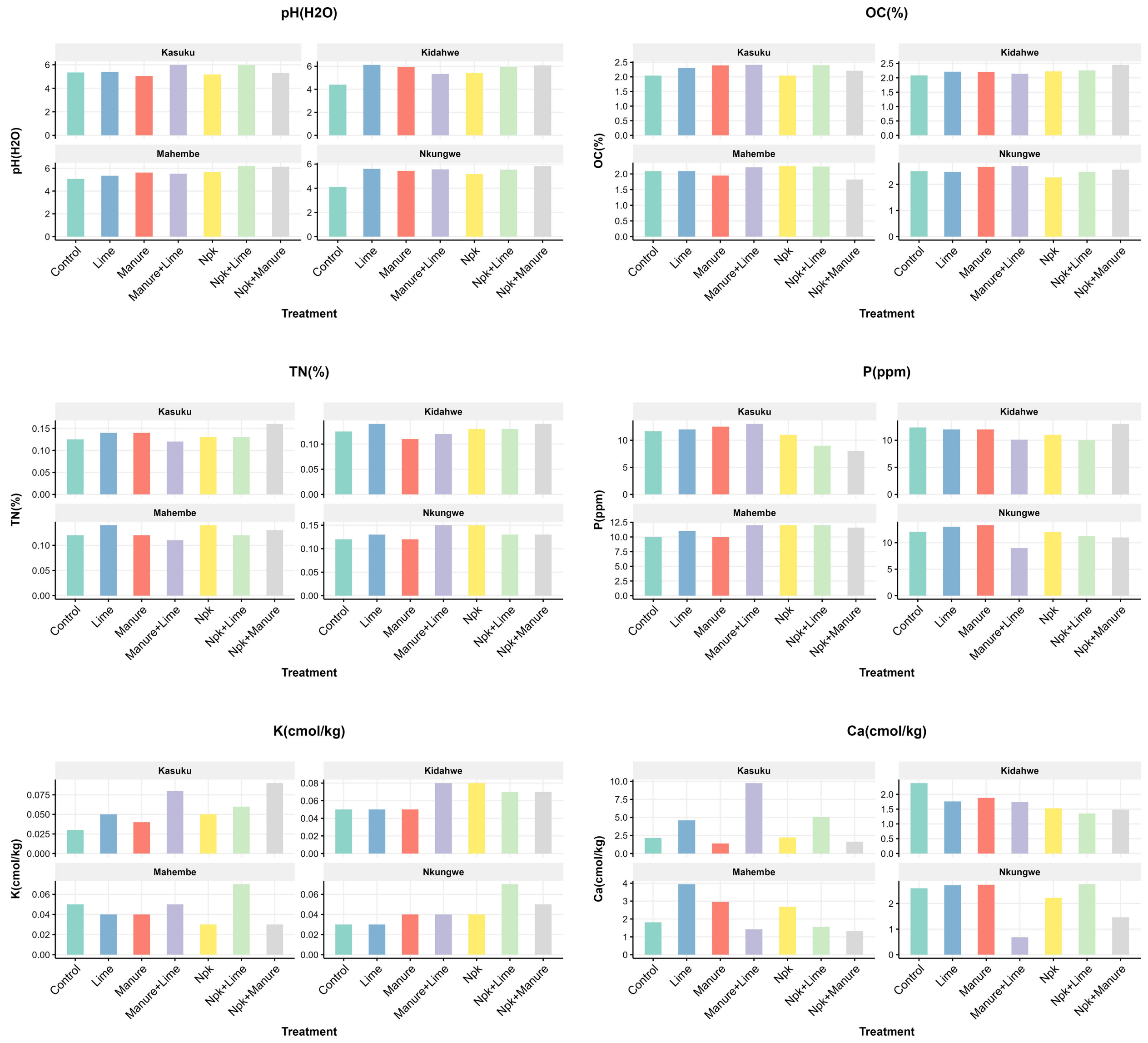

FIGURE 3
The bar graphs illustrate the impact of various treatments on soil fertility indicators.

3.5 Sensitivity analysis

Using actual maize production data from the study sites in the Kigoma District, we investigated the possibility of maize farmers maintaining positive net revenues despite increasing cost of production (for both organic and inorganic fertilizers). By examining the ISFM options considered in the study and incorporating yield effects and changes in production costs across options, a more realistic picture of a decrease in net revenues for each option was observed (Figure 7).

At a 1% increase in fertilizer prices, the use of lime + NPK resulted in the highest net return compared to other options such as lime + Manure, lime alone, and manure alone. However, as the rate of increase in fertilizer prices rose to 2% and above, the highest net revenue could be realized by farmers using lime in combination with manure, followed by those using lime and manure separately.

4 Discussion

4.1 Effects of treatment on soil pH and nutrient availability

The increase in pH could be attributed to neutralization of H^+ ions in the soil solution due to lime application (Khoi and Thom, 2015; Kisinyo et al., 2014; Chen et al., 2015; Kimiti, 2018; Mallarino, 2018; Corbett et al., 2021). The mechanism involves the dissociation of lime in the presence of water to Ca^{2+}, HCO3-, and OH^- ions, where H^+ ions are neutralized by HCO3- and OH^-, increasing soil pH. This shift towards neutral pH enhances the availability of base cations (Ca, Mg, and K), as documented by Qaswar et al. (2020); Mallarino (2018), and Tisdale et al. (2002). In addition, increased Ca^{2+} levels also result from the calcium present in the applied lime. Similarly, studies by Kisinyo et al. (2014); Chimdi et al. (2012);

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TABLE 6 Regression analysis on the effects of lime, manure, and NPK fertilizers on the soil's chemical properties.

Variable	pH	OC (%)	TN (%)	P (ppm)	K (cmol kg-^{1})	Ca (cmol kg-^{1})	Mg (cmol kg-^{1})
Intercept	4.699***	2.16***	0.13***	11.19***	0.05***	3.58***	0.70***
Site							
Kidahwe	0.14	-0.03	-0.007	0.47	0.007	-2.10*	-0.44*
Mahembe	0.19	-0.16	-0.009	0.21	-0.01	-1.59	-0.30
Nkungwe	-0.13	0.27**	-0.022	0.63	-0.01		
Treatment							
Lime	0.88**	0.09	0.015	0.49	0.002	1.02	0.09
Manure	0.77**	0.12	0.00	0.44	0.002	0.00	-0.04
Manure+lime	0.86**	0.19	0.002	-0.49	0.02*	1.16	0.21
NPK	0.62*	0.02	0.015	-0.01	0.01	-0.08	-0.08
NPK+lime	1.18***	0.17	0.005	-0.96	0.03**	0.44	0.04
NPK+manure	1.10***	0.08	0.018*	-0.61	0.02*	-0.76	-0.19

*p<0.05; **p<0.01; ***p<0.001.

TABLE 7 Effects of the treatments on maize growth performance and yields.

Analysis of variance									
Variable	DF	BgB (kg)	GWP (kg)	GWM (kg)	PH (cm)	CL (cm)	TSW (kg)	AgB (kg)	Yield (t h-^{1})
Replication	2	0.04	0.65	0.01	76.8	0.63	0	0.84	0.15
Treatment	6	1.26***	72.94***	0.87***	12192.1***	47.58***	0.03***	8.26***	17.16***
Site	3	2.33***	127.27***	1.58***	3590.5***	72.29***	0.03***	18.27***	31.05***
Treat × Site	18	0.18***	6.99***	0.08***	1210.9***	1.04**	0	0.97***	1.65***
Error	54	0.06	1.58	0.02	138.9	0.44	0	0.2	0.37
Site									
Mahembe		7.1^{a}	10.6^{b}	1.2^{b}	215.7^{a}	15.4^{ab}	0.33^{ab}	21.9^{a}	5.2^{b}
Nkungwe		6.9^{a}	5.2^{a}	0.6^{a}	246.0^{b}	13.8^{a}	0.28^{a}	24.2^{a}	2.5^{a}
Kidahwe		14.1^{b}	10.0^{b}	1.1^{b}	237.2^{ab}	17.0^{bc}	0.35^{b}	42.4^{b}	4.9^{b}
Kasuku		9.1^{a}	9.2^{b}	1.0^{a}	246.0^{b}	18.1^{c}	0.35^{b}	26.0^{a}	4.4^{b}
Treatment									
Control		0.52 ^{a}	4.82 ^{a}	0.53 ^{a}	166.50 ^{a}	12.70 ^{a}	0.26 ^{a}	2.06 ^{b}	2.36 ^{a}
Lime		0.64 ^{a}	7.73 ^{bc}	0.85 ^{bc}	222.60 ^{b}	15.42 ^{bc}	0.30 ^{b}	1.76 ^{a}	3.77 ^{bc}
Lime + Manure		0.72 ^{a}	8.36 ^{c}	0.92 ^{c}	239.80 ^{c}	14.90 ^{b}	0.30 ^{b}	2.68 ^{b}	4.08 ^{c}
NPK		1.00 ^{b}	10.16 ^{d}	1.11 ^{d}	255.10 ^{d}	17.35 ^{d}	0.36 ^{d}	3.23 ^{c}	4.95 ^{d}
Manure		1.02 ^{b}	7.17 ^{b}	0.79 ^{b}	233.80 ^{c}	15.93 ^{c}	0.32 ^{c}	2.81 ^{b}	3.49 ^{b}
NPK + manure		1.17 ^{b}	10.83 ^{d}	1.17 ^{d}	237.30 ^{c}	17.42 ^{d}	0.38 ^{e}	3.27 ^{c}	5.27 ^{d}
Lime + NPK		1.43 ^{c}	12.07 ^{d}	1.32 ^{e}	265.10 ^{e}	18.75 ^{e}	0.40 ^{e}	4.25 ^{d}	5.88 ^{e}
CV (%)		4.3	14.4	14.3	5.1	4.1	3.4	6	1.7
LSD		0.39	2.06	0.22	19.3	1.09	0.4	0.73	0.99
SE		0.19	0.73	0.08	6.81	0.38	0.1	0.26	0.35

Where: BgB, belowground biomass dry weight; AgB, aboveground biomass dry weight; TSW, thousand seed weight; CL, cob length; PH, plant height; GWM, grain weight per meter square; GWP, grain weight per plot.
The following p-values are significant: **p<0.01; ***p<0.001.
Mean followed by the same case lowercase letters are not significantly different at p<0.05.

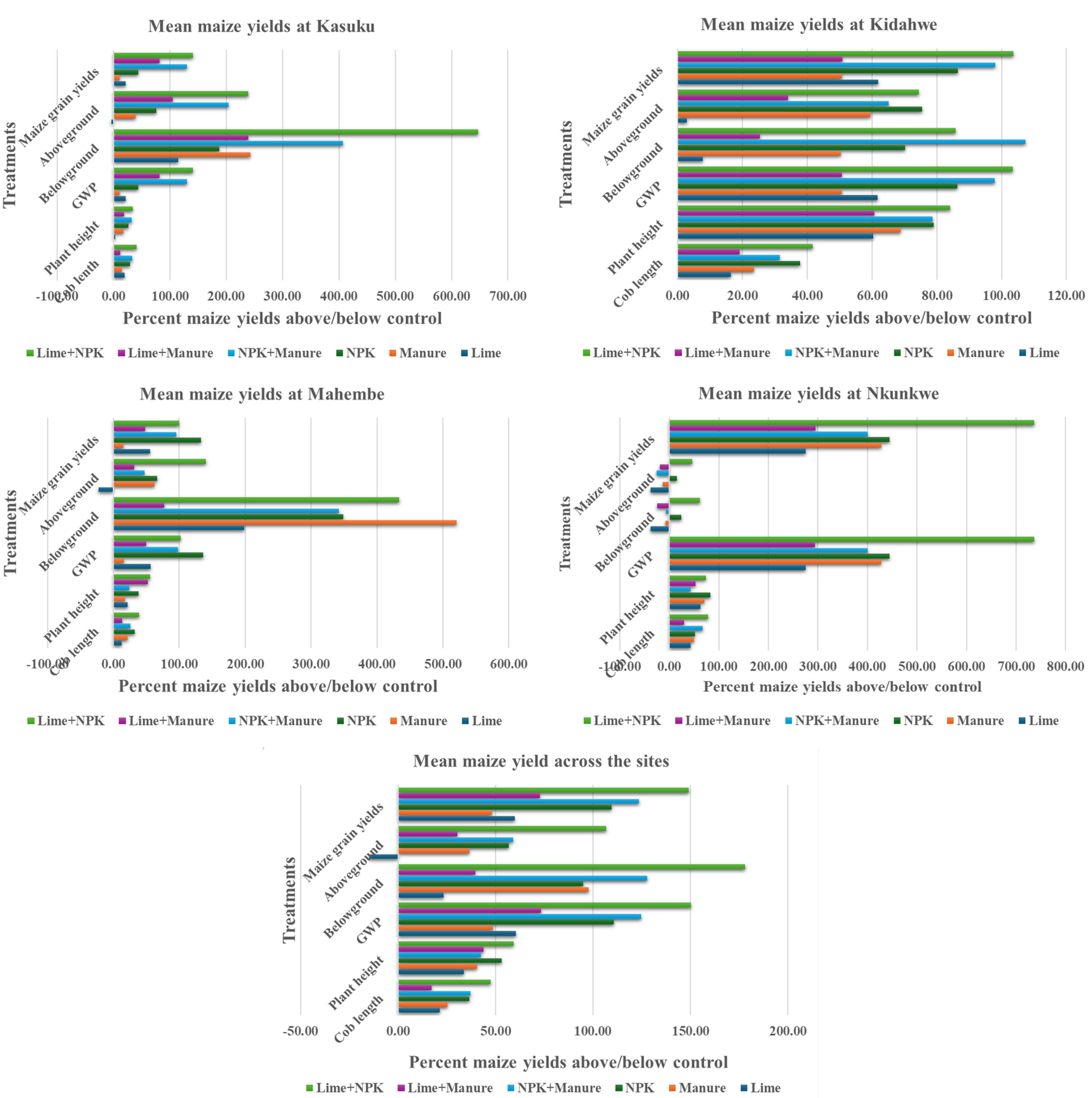

FIGURE 4
Effects of treatments on maize growth at different sites (Kasuku, Kidahwe, Mahembe, and Nkunkwe).

Verde et al. (2018), and Yaseen et al. (2024) confirm an increase in exchangeable Ca^{2+} following lime and fertilizer application.

Furthermore, manure application alone or in combination with lime enhances soil properties such as pH, Ca, Na, and microbial activities, as observed in studies by Qaswar et al. (2020); Otieno et al. (2018); Opala et al. (2018); Dhiman et al. (2019); Kisinyo et al. (2014); Chimdi et al. (2012), and Agbede et al. (2010). Manure and lime also improved available P levels, as increasing pH creates favorable conditions for P solubility (Yaseen et al., 2024; Verde et al., 2018; Kisinyo et al., 2014; Buni, 2014). The mechanism behind this is the release of exchangeable cations, potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^2+) during the decomposition of manure (Whalen et al., 2000). Additionally, Eghball et al. (2004) demonstrated that the buffering effect of manure plays a significant role in mitigating soil acidity. This effect is primarily facilitated through the decomposition process, where the presence of bicarbonates and organic anions contributes to the neutralization of soil acidity and helps stabilize soil pH levels. Their findings align with the current understanding that manure can act as an effective buffer, promoting a more stable and less acidic soil environment.

These cumulative benefits of manure, however, do not occur instantly but take time to manifest. Its gradual effects on soil fertility are due to its impact on physical structure, increasing microbial diversity and nutrient mineralization (Zingore et al., 2008). These benefits result in increased maize yields and sustainable agricultural productivity (Fan et al., 2020).

Application of 6t ha^{-1} of manure increased the CEC, resulting in increased base cations (Ca, Mg, and K) and available P, while reducing the toxicity level of Al and Mn (Ewulo, 2005). Similarly, Kheyrodin and Antoun (2011) documented improved soil fertility through nutrient addition, organic matter incorporation, and increased pH. However, recent studies by Tak et al. (2023) and

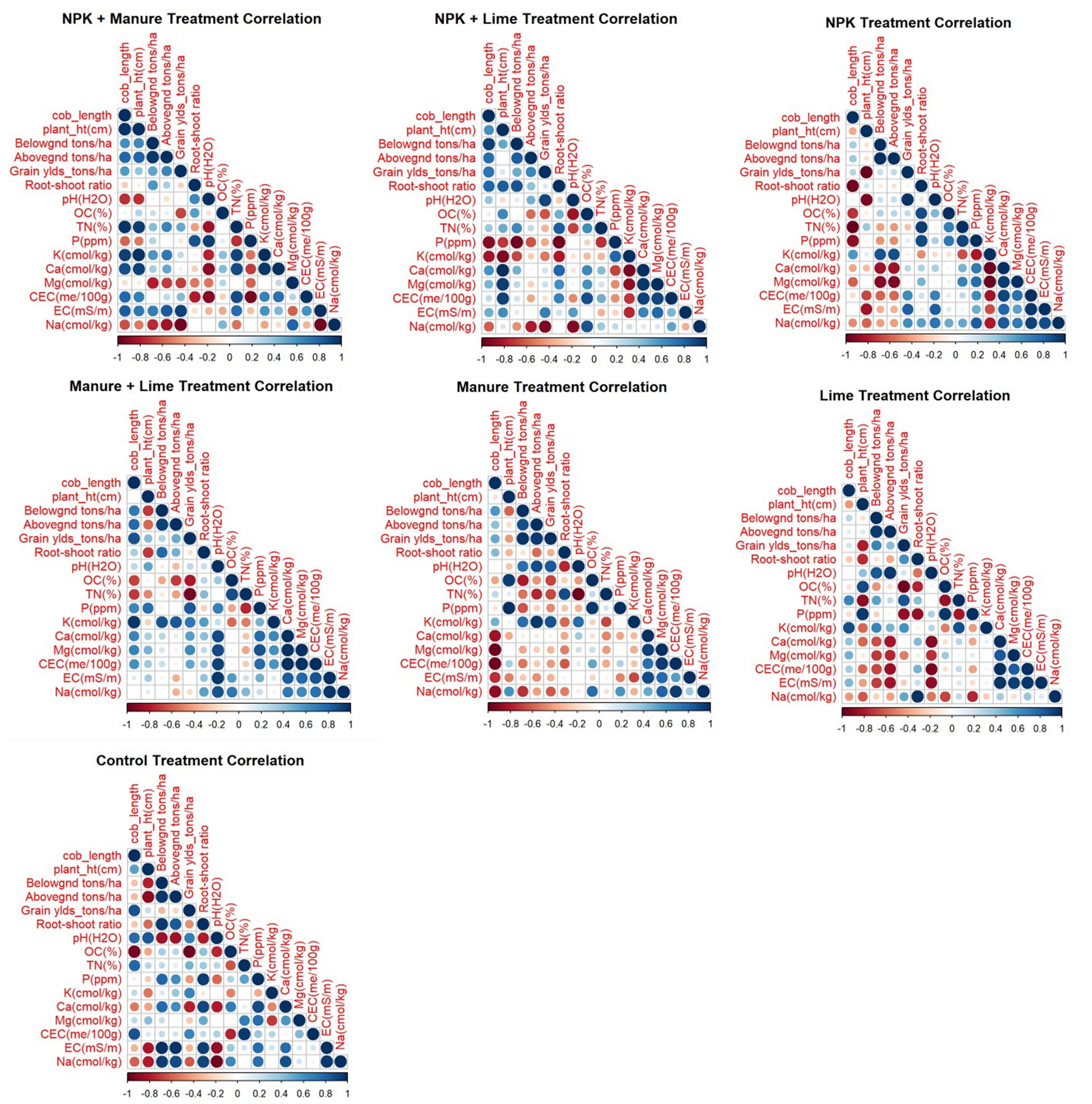

FIGURE 5
The correlations between different treatments and their effects on crop parameters and soil fertility indicators.

Cai et al. (2018) have further emphasized that the source and quality of manure play an important role in improving soil fertility and raising soil pH, confirming that manure's efficacy is highly dependent on its composition and treatment. Building on this, Kimiti (2018) and Azeez and van Averbeke (2012) confirm that the quality of manure determines its efficiency in increasing soil pH. This could explain why manure (5.51) had a low capacity for soil pH increase in comparison to lime (6.26). The studies by Mugwe et al. (2009) and Whalen et al. (2000) corroborate that the application of organic manure led to an increase in soil pH, which they attributed to buffering from bicarbonates and organic acids in cattle manure. A recent study by Shi et al. (2019) further corroborates this finding, showing that manure increased pH buffering capacity and the resistance of soil to acidification, resulting in stronger pH buffering. Furthermore, Kheyrodin and Antoun (2011); Adeniyan et al. (2011), and Agbede et al. (2010) documented that the use of manure and lime alone or in combination with fertilizers led to significant increases in Mg, Ca, and K, and resulted in reduced Mn toxicity in the soil. Recent research by Chen et al. (2021) and Verma et al. (2022) further validates these findings, showing that the combination of organic amendments with fertilizers improves nutrient cycling, reducing

TABLE 8 Cost (USD/ha) of maize production across the treatments.

Cost	Control	Lime	Manure	Lime + manure	NPK	NPK + manure	Lime + NPK
Fertilizer	0 (0)	0 (0)	0 (0)	0 (0)	202.5 (32.5)	202.5 (29.5)	202.5 (32.1)
Lime	0 (0)	8.6 (2.0)	0 (0)	8.6 (1.7)	0 (0)	0 (0)	8.6 (1.4)
Manure	0 (0)	0 (0)	64.4 (13.3)	64.4 (13.1)	0 (0)	64.4 (9.4)	0 (0)
Land prep	68.6 (16.3)	68.6 (16.0)	68.6 (14.2)	68.6 (13.9)	68.6 (11.0)	68.6 (10.0)	68.6 (10.9)
Seed	42.9 (10.2)	42.9 (10.0)	42.9 (8.9)	42.9 (8.7)	42.9 (6.9)	42.9 (6.2)	42.9 (6.8)
Planting	25 (6.0)	25 (5.8)	25 (5.2)	25 (5.1)	25 (4.0)	25 (3.6)	25 (4.0)
Weeding	137.3 (32.7)	137.3 (32.0)	137.3 (28.4)	137.3 (27.9)	137.3 (22.1)	137.3 (20.0)	137.3 (21.8)
Pesticides	17.2 (4.1)	17.2 (4.0)	17.2 (3.6)	17.2 (3.5)	17.2 (2.8)	17.2 (2.5)	17.2 (2.7)
Harvesting	42.9 (10.2)	42.9 (10.0)	42.9 (8.9)	42.9 (8.7)	42.9 (6.9)	42.9 (6.2)	42.9 (6.8)
Shelling	32.2 (7.7)	32.2 (7.5)	32.2 (6.7)	32.2 (6.5)	32.2 (5.2)	32.2 (4.7)	32.2 (5.1)
Packaging	32.2 (7.7)	32.2 (7.5)	32.2 (6.7)	32.2 (6.5)	32.2 (5.2)	32.2 (4.7)	32.2 (5.1)
Transport	21.5 (5.1)	21.5 (5.0)	21.5 (4.4)	21.5 (4.4)	21.5 (3.5)	21.5 (3.1)	21.5 (3.4)
Productioncost	419.8 (100)	428.4 (100)	484.2 (100)	492.8 (100)	622.3 (100)	686.7 (100)	630.9 (100)

Values in brackets are percentages of the total cost of production for each treatment. All the plots that received NPK were top dressed using urea.

toxic elements accumulations and promoting soil health. The comparison of the ANOVA and regression analyses revealed similarities and differences in the evaluation of the effect of the ISFM treatments on soil parameters. Both methods identified significant treatment effects on soil pH, phosphorus, and potassium, aligning with previous studies showing the positive effects of lime and nutrient management on soil fertility (Kisinyo et al., 2014). However, discrepancies were observed for OC and TN. While ANOVA detected significant effects of the ISFM treatments on OC, the regression analysis did not, suggesting that a site-specific factor, such as soil texture, may have had a greater influence on OC storage (Chivenge et al., 2007). The regression analysis identified a significant positive effect of the NPK + manure treatment on TN, which was not observed in the ANOVA results. This shows the advantage of regression analysis in elucidating treatment effects that account for site variability, which was not emphasized in ANOVA (Vanlauwe et al., 2010). Overall, the findings show the importance of using multiple statistical approaches to gain a comprehensive understanding of the effects of ISFM practices on soil properties.

In terms of organic carbon content, studies by Ndung'u et al. (2021) and Gram et al. (2020) documented that the application of manure + NPK significantly ($p < 0.05$) increased OC levels. This is

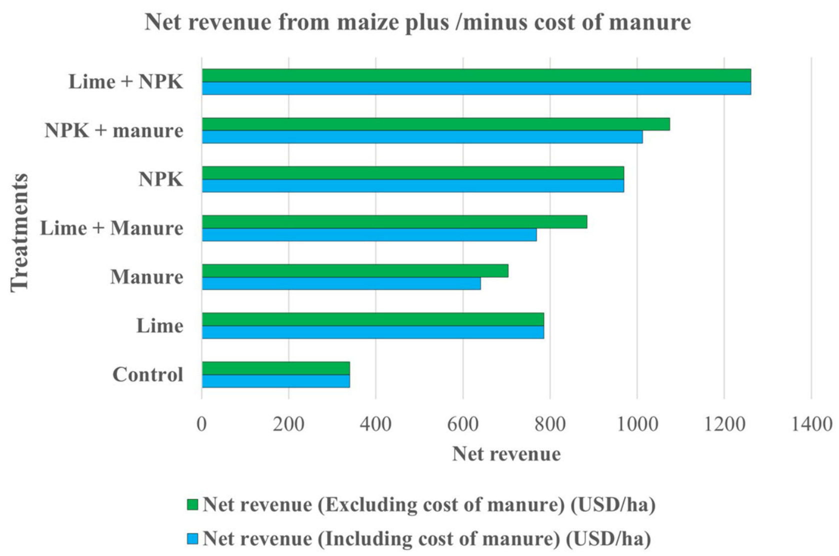

FIGURE 6
Net revenue from maize ± cost of manure.

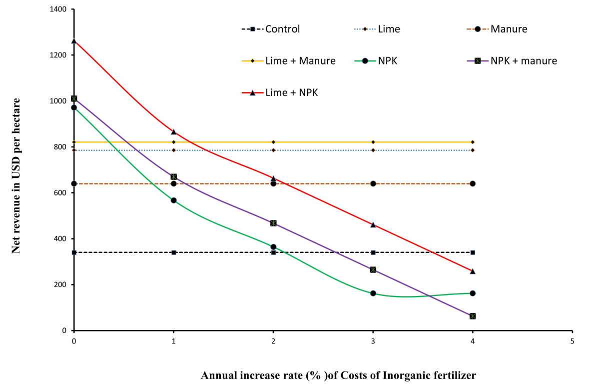

FIGURE 7
Sensitivity analysis of the cost of production (rate of increase in fertilizer prices).

consistent with findings from Sun et al. (2015) and Zhang et al. (2024), which revealed that soil amended with livestock composts either alone or in combination with inorganic fertilizer had improved enzyme activity and bacterial diversity in soils. A recent study by Das et al. (2023) confirmed that livestock composts are not only crucial for improving soil health but also significantly enhance carbon sequestration. Finally, Li et al. (2017) showed that the combined application of manure and NPK fertilizers increased OC and TN and enhanced the bacterial communities that play important roles in the decomposition of complex organic matter and in transformations of soil carbon, nitrogen, and phosphorus. Recent work by Zhang et al. (2024) also confirmed the synergistic effect of combining organic and inorganic amendments, showing that such practices can further enhance microbial resilience and nutrient cycling in the soils.

4.2 Effects of the treatments on maize yield and crop parameters

Kigoma soils are generally acidic, requiring an application of lime to improve the soil's chemical properties and consequently, enhance maize yield. Lime plays an important role in ameliorating the effects of aluminum ions in the soil (Muindi et al., 2015; Kisinyo et al., 2014). A study by Haling et al. (2010) has shown that soil acidity negatively affects root growth and soil nutrient sorption, which can lead to deficiencies in essential nutrients such as phosphorus and calcium. Lime increases soil pH, which facilitates aluminum hydrolysis, leading to precipitation as Al(OH)3 and resulting in an increase in CEC, thus making exchangeable base cations (K and Ca) more available (Tisdale et al., 2002). Additionally, an increase in pH enhances P availability, an important nutrient for maize production. Studies by Liang et al. (2021); Kimiti (2018); Sun et al. (2015), and Jabbar et al. (2022) have documented similar findings that lime application, especially when combined with manure and NPK fertilizers, significantly improves nutrient availability and maize yield. Similarly, Thakur et al. (2020) and Ayalew (2010) also observed a maize yield increase following the application of manure in combination with lime and mineral fertilizers.

Indeed, beyond the direct effects of lime, the integration of NPK fertilizers alongside lime forms an effective synergy that improves soil fertility and plant growth. The application of both lime and NPK has been shown to enhance a range of growth parameters, including BgB, aboveground AgB, PH, CL, and overall grain yield (Yield). Lime's effect on increasing soil pH not only facilitates the availability of nutrients but also enhances the efficacy of applied fertilizers by increasing the pH of the acidic soils (Tisdale et al., 2002). This synergy is evident in observed improvements in biomass production and the more robust root system, which are essential for nutrient uptake and overall plant growth (Haling et al., 2010). Moreover, the combination of lime and NPK fertilizers is an important strategy for addressing nutrient deficiencies in soils like those in Kigoma, which often limit the availability of nutrients such as P and Ca (Liang et al., 2021).

Site variability also played a substantial role in maize growth, with differences observed between locations such as Kidahwe, which had higher biomass production, and Kasuku, where plant height and cob length were superior. These differences highlight the importance of local soil conditions, such as soil texture and organic matter content, which can significantly influence the success of ISFM practices. A study by Jabbar et al. (2022) emphasized how localized characteristics, such as organic matter content and fertility, can impact fertilizer efficacy. Understanding site-treatment interactions can help tailor ISFM practices to specific regional conditions, thereby optimizing maize production in varying contexts.

The applications of manure, particularly when combined with lime and NPK, also contributed positively to maize growth. Manure improves soil structure, boosts microbial activity, and enhances nutrient cycling, thereby promoting sustained nutrient availability for maize plants. This aligns with findings by Thakur et al. (2020) and Ayalew (2010), who reported enhanced maize yield with the use of organic amendments. While manure alone improved maize growth, its combination with lime and NPK fertilizers produced even more significant results, emphasizing the synergistic effects of integrated nutrient management. Lime, by improving soil pH, likely unlocked the potential of organic amendments, facilitating better nutrient uptake.

The correlation analysis further compounds the importance of nutrient availability and soil fertility in driving maize growth, showing a strong relationship between plant height, biomass production, and nutrient levels in the soil. These findings emphasized the importance of soil amendments in improving soil health and enhancing maize productivity (Liang et al., 2021). Furthermore, understanding the role of decomposition of manure through microbial activities could offer further information on the mechanisms that lead to improved maize growth. A previous study by Sun et al. (2015) showed that microbial communities in organic-amended soils play a key role in nutrient cycling, which contributes to long-term improvements of soil fertility.

Therefore, the combined application of lime, NPK, and manure demonstrates an important strategy for improving maize growth in the acidic soils of the Kigoma region. Thus, by understanding these complex interactions, it is possible to utilize ISFM practices to maximize yields and improve the overall soil health, resulting in improved food security.

4.3 Cost effectiveness of inputs used for maize production

The continuous use of acidifying fertilizer has hampered agricultural productivity growth among smallholder farmers in Tanzania. This is partially because of the negative attitude and lack of awareness by farmers towards fertilizer application. Moreover, poor farm management practices in Kigoma have contributed to soil and land degradation. Restoring soil health over time is important for farmers aiming to improve their yields and income.

The lower net revenue in the Nkungwe site may largely be attributed to poor crop yields due to degraded soils and waterlogging, both of which reduce soil fertility and hinder proper crop growth. In contrast, the highest revenue was generated from plots treated with NPK + lime. This outcome can be explained by the positive impact of lime, which helped neutralize soil pH, providing nutrients such as phosphorus and base cations to plants. Furthermore, lime similarly creates a more conducive environment for soil organisms, enhancing the overall soil structure and fertility. Additionally, the NPK fertilizer provided essential macronutrients, further boosting maize productivity. Although the use of inorganic fertilizers, such as NPK, delivers quick results in the short term, it is important to acknowledge the rising costs of these inputs. These increases are driven by factors such as the devaluation of the Tanzanian shilling against major currencies, higher transportation costs, and global fertilizer price inflation. As a result, while inorganic fertilizer may be cost-effective in the short term, the long-term sustainability of its use remains uncertain.

In contrast, organic amendments, such as manure, may take longer for soil fertility improvements to take effect, but they offer a more sustainable and cost-effective solution over time. The incorporation of organic matter into the soil can gradually restore fertility and improve soil health. A study by Das et al. (2023) supports this, emphasizing that while the benefits of organic fertilizers, such as manure, may take longer to manifest, they contribute significantly to long-term soil fertility enhancement. Smallholder farmers in Kigoma, who often lack the financial resources to purchase inorganic fertilizers, could greatly benefit from relying more on organic inputs. Moreover, manure, which is typically available from livestock, represents a vital resource for farmers to reduce their reliance on expensive inorganic fertilizers. To reduce the cost of production, smallholder farmers are encouraged to keep livestock that produce manure at a lower cost for use on their farms.

This finding suggests that as fertilizer costs increase, there may come a point where their use is no longer economically viable for smallholder farmers. Consequently, different ISFM options, such as lime + manure and lime and manure alone, may provide a more economically sustainable solution. The findings of this study align with previous studies conducted by Jjagwe et al. (2020); Islam et al. (2019); Singh et al. (2019), and Naeem et al. (2006). Furthermore, these studies revealed that the use of organic amendments, e.g., manure and in combination with lime, had better soil performance than inorganic fertilizers, especially for soil fertility and sustainable crop productivity. Moreover, Das et al. (2023) emphasize the long-term benefits of manure in enhancing soil health and fertility. Therefore, adopting a combination of lime and manure could be a more cost-effective and environmentally sustainable approach for smallholder farmers in the region.

The sensitivity analysis presented in this study offers valuable insights into the future economic viability of different fertilizer strategies under varying price conditions. The analysis shows that if fertilizer prices increase by more than 2%, the use of lime combined with manure is the most cost-effective option. This suggests that the combination of organic inputs and lime can help farmers maintain higher net revenues, especially if organic inputs such as manure are incorporated into the farming system. The finding aligns with the broader literature on the cost-effectiveness of ISFM. Studies have shown that the ISFM approach not only enhances soil fertility but also improves the economic sustainability of farming systems in the long run (Jjagwe et al., 2020; Islam et al., 2019; Singh et al., 2019). As fertilizer costs continue to rise, smallholder farmers who adopt ISFM practices could be better positioned to maintain profitability. Inorganic fertilizers offer short-term benefits but their rising costs may make them less viable in the future. The adoption of organic inputs, particularly manure, alongside lime provides a more sustainable and cost-effective approach for smallholder farmers. Over time, organic amendments such as manure will improve soil fertility, leading to increased yields and reduced dependency on expensive fertilizers (Luo et al., 2018).

5 Conclusion

The study offers valuable insights on the influence of ISFM practices on soil chemical properties, maize growth performance, and economic returns in the region. The findings reinforce the important role of ISFM in addressing soil acidity and nutrient deficiencies. Specifically, the combination of lime and manure significantly improved soil pH, electrical conductivity, cation exchange capacity, and exchange calcium, which translated to enhanced maize growth and yield. The application of lime and NPK fertilizer resulted in the highest maize yields, demonstrating a 149% increase over the control treatments. The economic analysis revealed that while inorganic fertilizers remain costly, the use of manure and lime presents a more economically viable and sustainable alternative. This finding is of particular importance for smallholder farmers, as it offers pathways to improve productivity and profitability in the face of rising fertilizer costs. The sensitivity analysis further indicated the growing challenges posed by increasing fertilizer costs and supports the integration of organic inputs as a cost-effective and sustainable solution.

Given these findings, future research should focus on the long-term effects of ISFM practices, particularly the co-application of lime and manure on soil health and productivity under varying climatic conditions. Studies examining the optimal application rates of lime and manure and exploring synergies with other sustainable soil management practices would provide a deeper understanding, maximizing the benefit of ISFM. In addition, research into the socioeconomic barriers to widespread adoption of other practices among smallholder farmers, along with strategies to enhance their accessibility, would be valuable for scaling up ISFM adoption in developing regions. Ultimately, these efforts will contribute to the growing body of knowledge on sustainable agricultural practices and lay a foundation for promoting the use of ISFM approaches to improve soil fertility, crop productivity, and farmer profitability within resource-constrained smallholder farming systems in sub-Saharan Africa.

5.1 Study limitations

Our study was designed to fit a 1-year time frame allocated by the donor. The first phase involved conducting workshops to co-develop the research design with the stakeholders, while the second phase focused on implementing the trial at four sites. As such, the study was constrained to a single year, which restricted the possibility of collecting data across multiple seasons.

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 were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MSS: Project administration, Data collection, Data curation, Data validation, Formal analysis, Investigation, Methodology, Writing-original draft, Writing-review and editing: DKL: Conceptualization, Project administration, Supervision, Data curation, Data validation, Formal analysis, Investigation, Methodology, Data validation, Fund Acquisition, Visualization, Writing-original draft, Writing-review and editing: NMK: Formal analysis, Investigation, Validation, Visualization, Writing-review and editing: LNM: Formal analysis, Investigation, Methodology, Visualization, writing-review and editing: FS: Funds acquisition, Writing-review and editing.

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Conflict of interest

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

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher’s note

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