

Influence of Cover Crops and Nitrogen Fertilization on Soil Health under Maize Cropping System in Sudan Savannah of Nigeria

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Abstract

This study evaluated the influence of selected leguminous cover crops and nitrogen fertilization on soil health under a maize cropping system in the Sudan Savannah of Nigeria. The experiment was conducted using a randomized complete block design (RCBD) comprising four cover crop treatments (Mucuna, Lablab, Cowpea, and control) and five nitrogen rates (0, 30, 60, 90, and 120 kg N ha⁻¹), replicated three times. Key soil health indicators assessed included soil pH, organic carbon (OC), organic matter (OM), total nitrogen (TN), available phosphorus (AvP), exchangeable bases, micronutrients, and salinity parameters. Results showed that cover crops significantly improved OC and OM compared to sole maize ($p < 0.05$), with Lablab and Mucuna recording values above 2.8% and 4.8%, respectively. Total nitrogen and available phosphorus were also significantly enhanced under legume-based systems, particularly maize–Mucuna ($p < 0.05$). Nitrogen fertilization significantly increased TN ($p < 0.05$), although higher rates slightly reduced AvP. Significant interaction effects between cover crops and nitrogen were observed for TN and AvP ($p < 0.05$), indicating synergistic benefits. Micronutrients, especially Fe and Mn, were significantly improved under cover crops ($p < 0.05$), while salinity indices remained within safe limits. Integrating leguminous cover crops with moderate nitrogen fertilization enhances soil fertility and nutrient dynamics, supporting sustainable maize production in the Sudan Savannah.

Keywords: Cover Crops, Cropping System, Maize, Nitrogen Fertilization, Soil Health, Sudan Savannah.

Introduction

Agricultural sustainability is increasingly threatened by soil degradation, particularly in monoculture systems such as continuous maize (*Zea mays* L.) cultivation. This degradation manifests in various forms, including reduced soil fertility, organic matter depletion, compaction, and erosion, all of which contribute to declining crop yields and environmental quality (Lal, 2020). One promising approach to mitigate these issues is the use of cover crops, particularly leguminous species, within cropping systems. Cover crops have gained significant attention due to their potential to enhance soil health, which is a crucial component of sustainable agriculture (Blanco-Canqui and Ruis, 2020). Cover crops, such as Mucuna (*Mucuna pruriens*), Lablab (*Lablab purpureus*), and Cowpea (*Vigna unguiculata*), are particularly valuable in improving soil health due to their nitrogen-fixing abilities,

capacity to add organic matter to the soil, and effectiveness in preventing soil erosion (Carsky et al., 2001; Thierfelder and Wall, 2010). These benefits are especially important in maize-based cropping systems, where continuous maize cultivation can lead to significant soil nutrient depletion and reduced soil structure (Franzluebbers, 2020). The integration of cover crops into these systems offers a sustainable solution to enhance soil fertility, structure, and biological activity.

Mucuna, known for its rapid biomass production and effective weed suppression, has been widely recognized for its ability to improve soil properties and crop productivity. Studies have shown that Mucuna can significantly increase soil organic matter, enhance nutrient cycling, and suppress weeds, leading to improved yields in subsequent maize crops (Sanginga and Woomer, 2009). Lablab and Cowpea, on the other hand, are not only efficient nitrogen fixers but also contribute to soil health by improving soil structure and increasing microbial activity. These leguminous cover crops can provide substantial quantities of nitrogen, which is crucial for maize growth, thereby reducing the need for synthetic fertilizers and enhancing soil fertility in the long term (Chikowo et al., 2010).

In recent years, there has been a growing body of research highlighting the multiple ecosystem services provided by cover crops, particularly in maize cropping systems. Cover crops have been shown to reduce soil erosion, improve water infiltration, and enhance soil organic carbon, which are all essential for maintaining soil health and ensuring sustainable crop production (Basche et al., 2016; Blanco-Canqui et al., 2015). Moreover, the use of leguminous cover crops can lead to a more resilient agroecosystem by increasing biodiversity and promoting beneficial soil organisms, which in turn can improve soil structure and nutrient availability (Snapp et al., 2005). The interaction between different cover crops and their cumulative effects on soil health is an area of ongoing research. For instance, Schipanski et al. (2014) demonstrated that using a mix of cover crops could lead to greater improvements in soil properties compared to monocropping systems. The inclusion of multiple cover crops, such as Mucuna, Lablab, and Cowpea, in a maize cropping system may provide synergistic benefits that enhance soil health more effectively than a single cover crop. These benefits include increased nitrogen availability, improved soil structure, and enhanced microbial activity, all of which contribute to better crop performance and soil conservation.

However, the effectiveness of cover crops in improving soil health can vary depending on factors such as soil type, climate, and management practices (Daryanto et al., 2018). Therefore, understanding the specific contributions of different cover crops to soil health under various agroecological conditions is crucial for optimizing their use in maize cropping systems. This study aims to investigate the influence of Mucuna, Lablab, and Cowpea on soil health under a maize cropping system, providing insights into how these cover crops can be effectively integrated to enhance soil fertility, improve maize yields, and promote sustainable agriculture.

Objectives

The main objective of this study was to evaluate the combined influence of selected leguminous cover crops and nitrogen fertilization on soil health under a maize cropping system in the Sudan Savannah of Nigeria. Specifically, the study aimed to: (i) quantify the effects of different cover crop species (*Mucuna*, *Lablab*, and *Cowpea*) on key soil health indicators, including soil organic carbon, organic matter, total nitrogen, and available phosphorus; (ii) determine the response of these soil properties to varying nitrogen fertilizer rates (0–120 kg N ha⁻¹); (iii) assess the interaction effects between cover crops and nitrogen fertilization on micronutrient availability, exchangeable bases, and salinity indices; and (iv) identify the most effective combination of cover crop and nitrogen rate for improving soil fertility in degraded sandy loam soils. These objectives provide measurable benchmarks for evaluating treatment effects and generating evidence-based recommendations for sustainable soil management in smallholder maize production systems.

Statement of the Problem

Declining soil fertility remains a major constraint to sustainable maize production in the Sudan Savannah of Nigeria, particularly among smallholder farmers cultivating degraded sandy loam soils. These soils are typically characterized by low organic matter, poor nutrient retention, and rapid nutrient depletion due to continuous cropping and inadequate soil management practices. Although mineral nitrogen fertilization is widely used to boost maize productivity, its effectiveness is often limited by low soil organic carbon and imbalanced nutrient dynamics, which can reduce nutrient use efficiency and accelerate soil degradation over time.

Leguminous cover crops have been widely reported to improve soil fertility through biological nitrogen fixation, organic matter addition, and enhanced nutrient cycling. However, despite these known benefits, there remains a critical gap in location-specific, quantitative evidence on how different cover crop species interact with varying nitrogen fertilizer rates to influence soil health indicators under maize-based systems in the Sudan Savannah. In particular, limited information exists on the combined effects of these practices on key soil properties such as organic carbon, nutrient availability, micronutrient dynamics, and salinity indices in degraded sandy loam soils.

This lack of integrated knowledge constrains the development of efficient and site-specific soil fertility management strategies for smallholder maize farmers in the region. Therefore, this study was undertaken to evaluate the interactive effects of selected leguminous cover crops and nitrogen fertilization on soil health, with the aim of providing evidence-based recommendations for sustainable soil management and improved maize productivity.

Research Questions

This study was guided by the following research questions designed to address key gaps in soil fertility management in the Sudan Savannah: (i) To what extent do different

leguminous cover crops (Mucuna, Lablab, and Cowpea) influence soil health indicators such as organic carbon, organic matter, total nitrogen, and available phosphorus under a maize-based system? (ii) How do varying nitrogen fertilizer rates (0–120 kg N ha⁻¹) affect soil nutrient dynamics and salinity parameters in degraded sandy loam soils? (iii) Are there significant interaction effects between cover crop species and nitrogen fertilization on soil chemical properties, including micronutrients and exchangeable bases? (iv) Which combination of cover crop and nitrogen rate provides the most sustainable improvement in soil fertility for smallholder maize production? These questions establish a clear analytical framework and ensure that the study's findings directly respond to the identified problem and support evidence-based soil management decisions.

Hypothesis

This study was based on the hypothesis that the integration of leguminous cover crops with nitrogen fertilization will significantly improve soil health indicators in degraded sandy loam soils under a maize cropping system. It is specifically hypothesized that: (i) leguminous cover crops (Mucuna, Lablab, and Cowpea) will increase soil organic carbon, organic matter, total nitrogen, and available phosphorus compared to the control (sole maize); (ii) increasing nitrogen fertilizer rates (0–120 kg N ha⁻¹) will enhance total nitrogen but may have diminishing or negative effects on available phosphorus at higher application levels; (iii) there will be significant positive interaction effects between cover crop type and nitrogen rate on soil nutrient status, micronutrient availability, and exchangeable bases; and (iv) combined application of leguminous cover crops and moderate nitrogen rates will produce greater improvements in soil health indicators than either practice applied alone. These hypotheses are grounded in established evidence that legume-based systems enhance nutrient cycling and soil organic matter, while integrated nutrient management improves soil fertility and sustainability.

Conceptual Framework

This study is grounded in the principles of integrated soil fertility management (ISFM) and agroecosystem nutrient cycling theory, which posit that combining organic and inorganic nutrient sources enhances soil productivity more effectively than either input alone. Leguminous cover crops contribute to soil health through biological nitrogen fixation, biomass addition, and stimulation of microbial activity, thereby increasing soil organic matter and improving nutrient retention. In contrast, mineral nitrogen fertilization provides readily available nutrients that support immediate crop growth but may have limited long-term benefits when applied in isolation, particularly in degraded sandy loam soils with low organic carbon.

This assumes that soil health is a function of synergistic interactions between cover crop type and nitrogen rate, influencing key indicators such as soil organic carbon, total nitrogen, available phosphorus, micronutrients, and salinity parameters. It further predicts that moderate nitrogen application, when integrated with leguminous cover crops, enhances nutrient cycling efficiency and reduces nutrient losses.

This framework directly informs the study's analytical approach, where a factorial arrangement within a randomized complete block design (RCBD) is used to test main and interaction effects of cover crop species and nitrogen rates on soil properties. The use of analysis of variance (ANOVA) enables evaluation of these effects, providing empirical validation of the proposed relationships.

Materials and Method

Experimental Site

The study was conducted on an experimental farm located in Professor Lawal Abdu Salawa Teaching and Research Farm, situated in Dutsin- Ma Local Government Area, Katsina State, Nigeria. The area experiences a tropical savannah climate, receiving about 800 mm of rain each year, with temperatures generally ranging between 25°C and 30°C. The site was prepared following standard agronomic practices, including land clearing, plowing, and harrowing, to ensure uniformity across plots. Each plot was assigned treatments with different cover crops, under maize cropping, to assess their impact on soil health.

Experimental Material

The materials used in this study include selected cover crop seeds (legumes like Mucuna, Lablab and Cowpea) and maize seeds, which were planted in designated plots. Inorganic fertilizers were applied as needed to support crop growth: urea was used as a nitrogen source, and single superphosphate was used as source of phosphorus. Additional materials include soil sampling tools for collecting soil samples at different growth stages, moisture meters, and laboratory equipment for analyzing soil health parameters such as organic matter, pH, nutrient content, and microbial activity. Fertilizers and pesticides was applied according to recommended agricultural practices for maize in in Dutsin-Ma Local Government area.

Experimental Design

The experiment was laid out in a randomized complete block design (RCBD) with three blocks (replicates). Treatments consisted of a factorial combination of four cover crop options (Mucuna, Lablab, Cowpea, and a no-cover crop as control) and five nitrogen fertilizer rates (0, 30, 60, 90, and 120 kg N ha⁻¹), resulting in a total of 20 treatment combinations. Each treatment was randomly assigned within each block, giving a total of 60 experimental plots. This design was used to control for spatial variability across the field and to allow for the evaluation of both main and interaction effects of cover crops and nitrogen fertilization. The selected nitrogen fertilizer rates (0, 30, 60, 90, and 120 kg N ha⁻¹) were based on established recommended rate of Fertilizer for maize production in the Nigerian Sudan Savannah which is 120 kg N ha⁻¹, this research looks at lower rates since leguminous cover crops were known to fix atmospheric nitrogen to find out which and the lower rate will improve soil health under maize cropping system.

Soil Sampling and Preparation

Three soil samples were taken using an M-shaped pattern from the site prior to planting, drilling down to 30 cm to capture a representative portion of the field. The samples were air-dried, lightly crushed, and sieved through a 2 mm mesh to remove coarse materials. After preparation, they were kept in clean, airtight containers until laboratory analysis. These samples were later examined for key soil characteristics such as organic matter, pH, nutrient status serving as baseline information before planting.

Soil Analysis

The soil analysis this research involved a series of laboratory procedures aimed at assessing major soil health indicators under the different treatments. Soil pH was determined in a 1:2.5 soil-to-water suspension using a pH meter following McLean (1982), providing insight into soil acidity or alkalinity and its effects on nutrient availability and microbial activity. Electrical conductivity was measured in a similar soil–water extract according to Rhoades (1996) to estimate the concentration of soluble salts that may influence plant growth. Total nitrogen was analysed using the Kjeldahl method as described by Bremner and Mulvaney (1982), allowing evaluation of nitrogen present in both organic and inorganic forms. Available Phosphorus was extracted using Brya-I extracting solution and read using Spectrophotometer following Bray and Kurtz (1945). Soil organic carbon was assessed using the Walkley–Black wet oxidation procedure outlined by Nelson and Sommers (1982), offering an understanding of soil organic matter levels and their contribution to fertility, structure, and moisture retention. Exchangeable bases; Calcium, Magnesium, Potassium, and Sodium were extracted with ammonium acetate and quantified using atomic absorption spectrophotometry following Thomas (1982) to determine their role in nutrient supply and cation exchange potential. Exchangeable acidity, including aluminium and hydrogen ions, was measured by titration with KCl solution in line with Thomas (1982) to evaluate potential acidity and its impact on soil chemistry. Cation exchange capacity was then calculated by summing exchangeable bases and acidity as described by Sumner and Miller (1996).

Soil micronutrients (Fe, Mn, Zn, and Cu) were extracted using the diethylenetriaminepentaacetic acid (DTPA) extraction method; were air-dried soil samples were extracted with a DTPA solution (0.005 M DTPA, 0.01 M CaCl_2 , and 0.1 M triethanolamine, adjusted to pH 7.3), the extracts were filtered and analyzed using an atomic absorption spectrophotometer (AAS) to determine the concentrations of the micronutrients. This method was selected due to its suitability for estimating plant-available micronutrients in neutral to slightly acidic soils.

Agronomy Practices

In this study, agronomy practices were implemented to enhance soil health and optimize maize growth within the cover crop system. Key practices included soil preparation through tillage to create suitable planting beds, nutrient management with inorganic fertilizers (urea as a nitrogen source and single superphosphate for phosphorus), and cover cropping.

Cover crops were planted to improve soil structure, prevent erosion, and increase organic matter content. Weed and pest management was conducted as needed to protect crops. These practices aimed to improve soil health indicators, which were measured throughout the experiment to assess the impact of cover crops within the maize cropping system.

Results and Discussion

Characteristics of the experimental soil

The baseline soil data of the experimental site is presented in Table 1. The soil texture is predominantly sandy, with sand content ranging from 55% to 63% and a mean value of 58.50%. This clearly indicates a sandy loam soil typical of many areas in the Sudan Savannah. Such soils generally have weak structural stability and tend to lose nutrients quickly due to leaching. The proportion of silt (21–30%, mean 26.50%) and clay (14–16%, mean 15.00%) confirms the light-textured nature of the soil, which often translates into low water retention and limited nutrient-holding capacity (Inuwa et al., 2024; Sani et al., 2022). These characteristics point to the need for management practices that build organic matter and improve aggregation roles that cover crops are well known to support through root development and residue incorporation (Adesoji et al., 2025). This pH range falls within a generally acceptable level for maize and many soil microorganisms which is in accordance with the findings of Abdulkadir et al., (2022), although acidity at this level may slightly reduce the availability of certain nutrients, particularly phosphorus (Sposito, 2016). The electrical conductivity was extremely low, averaging 0.02 dS/m, which indicates that the soil has no salinity issues. This is favorable for nutrient uptake and ensures that salt stress will not interfere with plant growth or microbial activity during the study (Khan et al., 2022; Dawaki et al 2019).

Organic carbon values were notably low, with a mean of 0.57% and a wide range of 0.34–1.03%. These figures reflect the naturally low organic matter content of many savannah soils, which is often a result of high temperatures, rapid decomposition, and limited biomass return. The variability in organic carbon further suggests inconsistent distribution of organic residues across the field (Habib et al., 2025; Sani et al., 2025; Abdulkadir et al., 2020). Total nitrogen levels were also low (0.04–0.06%, mean 0.05%) with a very high coefficient of variation, emphasizing nitrogen as a major yield-limiting factor for maize. These conditions strongly justify the introduction of nitrogen-fixing cover crops, which can help replenish nitrogen reserves while simultaneously improving soil structure and microbial activity (Abdulkadir et al., 2025a; Fawole et al., 2025).

Phosphorus content ranged widely from 0.89 to 6.65 mg/kg (mean 3.24 mg/kg), indicating a general deficiency commonly found in weathered tropical soils. The modest availability of exchangeable cations such as Ca (1.76–2.67 cmol/kg), Mg (0.53–0.83 cmol/kg), K (0.22–0.33 cmol/kg), and Na (0.07–0.12 cmol/kg) reflects the soil's relatively weak nutrient reserves which is in accordance with the findings of Abdulkadir et al., (2025b). The low exchangeable acidity values (0.00–0.05 cmol/kg) are a positive feature, indicating that aluminum toxicity is unlikely to hinder root development or microbial processes.

Meanwhile, the effective cation exchange capacity (ECEC), which averaged 3.24 cmol/kg, was low. This is consistent with the sandy texture and low organic matter levels, reinforcing the need to enhance soil carbon through cover crop biomass (Aliyu et al., 2024; Sani et al., 2024; Abdulkadir et al 2025a).

Micronutrient levels showed moderate consistency. Zinc values ranged from 4.50 to 5.00 mg/kg, copper from 2.26 to 2.93 mg/kg, manganese from 18.95 to 31.41 mg/kg, and iron from 107.52 to 133.20 mg/kg. These levels fall within acceptable ranges for maize nutrition, although their availability may shift depending on pH and organic matter changes over time (Adesoji et al., 2025).

The soil characteristics shows that the soil require significant improvement. The combination of low organic matter, limited nitrogen, weak phosphorus availability, and low CEC highlights the central challenges facing maize production in the Sudan Savannah. Incorporating cover crops into the system offers a practical pathway to address these constraints (Abdulkadir et al., 2025; Wopereis et al., 2006). Their biomass can enrich organic matter, enhance nutrient recycling, improve water retention, and support soil biological health. When complemented with appropriate nitrogen fertilization, these practices can improve soil function and productivity in a sustainable and long-term manner (Ekyaligonza et al., 2022).

Table 1: Characteristics of the experimental Soil

	Minimum	Maximum	Mean	Std. Deviation	Coefficient of variation (%)
Sand (%)	55	63	58.50	3.32	14.62
Silt (%)	21	30	26.50	3.873	5.44
Clay (%)	14	16	15.00	.816	2.25
pH (1:2.5)	5.60	5.93	5.77	0.13	50
EC(dS/m)	.01	.03	0.02	0.01	56.14
O.C (%)	0.34	1.03	0.57	0.32	20
N (%)	0.04	0.06	0.05	0.01	76.23
P (mg/kg)	0.89	6.65	3.24	2.47	18.69
Ca (cmol+)/kg)	1.76	2.67	2.14	0.40	17.14
Mg (cmol+)/kg)	0.53	0.83	0.70	0.12	18.52
K (cmol+)/kg)	0.22	0.33	0.27	0.05	20
Na (cmol+)/kg)	0.07	0.12	0.10	0.02	66.67
EA (cmol+)/kg)	0.00	0.05	0.03	0.02	9.24
ECEC (cmol+)/kg)	2.94	3.57	3.24	0.30	4.63
Zn (mg/kg)	4.50	5.00	4.75	0.22	11.11
Cu(mg/kg)	2.26	2.93	2.70	0.30	21.18
Mn (mg/kg)	18.95	31.41	25.50	5.40	10.4
Fe (mg/kg)	107.52	133.20	116.83	12.15	5.68

Influence of Cover Crops and Nitrogen Fertilization on Soil pH and Organic Carbon in a Maize Cropping System in Dutsin-Ma

Table 2 presents the outcomes of an experiment designed to assess the impact of different cover crops combined with varying nitrogen (N) fertilizer application rates on soil pH, organic carbon (OC), and organic matter (OM) content in a maize cropping system in Dutsin-Ma. This investigation aimed to determine how the integration of biological soil amendments through cover cropping and chemical inputs via nitrogen fertilization influences soil chemical properties that are critical for maintaining soil fertility and promoting sustainable agricultural productivity.

The application of different cover crops and nitrogen fertilization levels had notable effects on soil pH, organic carbon (OC), and organic matter (OM) within the maize cropping system in Dutsin-Ma. Soils where Lablab and Mucuna were used as cover crops recorded significantly higher levels of organic carbon (2.859% and 2.812%, respectively) and organic matter (4.917% and 4.837%), compared to the control which showed much lower values (1.690% OC and 2.907% OM). These results underscore the role of leguminous cover crops in enriching the soil through organic inputs and microbial stimulation, which leads to improved organic carbon pools. This aligns with the findings of Nyabami et al. (2024) and Abdulkadir et al., (2020), who emphasized the ability of legume cover crops to enhance soil organic content due to their rapid biomass decomposition and nitrogen fixation.

Soil pH was also influenced by both the type of cover crop and nitrogen application rate. Among the cover crops, Mucuna caused a slight acidification of the soil (pH 4.760), whereas Cowpea maintained a more neutral condition (pH 4.960). The variations in pH could be linked to the nature of root exudates and the decomposition process, which differ among cover crop species. On the nitrogen side, the N60 treatment recorded the highest pH (4.967), suggesting that moderate nitrogen rates may help buffer soil acidity. This is consistent with research by Souza et al. (2023) and Abdulkadir et al., (2025b), who noted that moderate nitrogen application improves nutrient cycling while maintaining favorable soil pH levels.

Interestingly, organic carbon and organic matter did not show statistically significant differences across nitrogen fertilization levels, indicating that nitrogen alone may not be a sufficient driver of soil organic buildup in the short term. This slightly contrasts with the findings of Blanco-Canqui and Jasa (2019), who found marginal increases in soil organic matter under long-term nitrogen fertilization, though soil texture and cropping system played a critical role.

Although the interaction between cover crops and nitrogen fertilization (CxN) was noted in the dataset, the specifics were not detailed. Nevertheless, several studies have reported synergistic effects when combining legume-based cover crops with moderate nitrogen inputs. For example, Souza et al. (2023) demonstrated enhanced microbial activity and improved nutrient cycling when both components were integrated in tropical soils.

Table 2: Influence of Cover Crops and Nitrogen Fertilization on Soil pH and Organic Carbon in a Maize Cropping System in Dutsin-Ma

COVER CROPS	PH	OC	OM
Control	4.940 a	1.690 b	2.907 b
Cowpea	4.960 a	2.775 a	4.773 a
Lablab	4.905 a	2.859 a	4.917 a
Mucuna	4.760 b	2.812 a	4.837 a
SED	0.0441	0.1835	0.316
N RATES			
0 kgN/ha	4.864 ab	2.443	4.201
30 kgN/ha	4.825 b	2.658	4.572
60 kgN/ha	4.967 a	2.454	4.221
90 kgN/ha	4.917 ab	2.657	4.570
120 kgN/ha	4.883 ab	2.458	4.228
SED	0.0493	0.189	0.326
INTERACTION			
CxN	**	ns	ns
C = Cover crops, N= Nitrogen Fertilizer Rate, ns = Not significant			

Interaction effect of Cover Crops and Nitrogen (N) Fertilizer Rates on Soil pH in Dutsin-Ma, Katsina State

Table 3 shows the interaction between different cover crop systems and nitrogen fertilizer rates on soil pH in Dutsin-Ma, Katsina State. The results indicate that both nitrogen application rate and the type of cover crop influenced soil pH, although the values generally remained within a moderately acidic range (about 4.5–5.3). The highest soil pH value (5.27) was observed in the maize + lablab treatment at 90 kg N/ha, suggesting that this combination had a relatively stronger buffering effect on soil acidity compared with other treatments. In contrast, the lowest pH value (around 4.5) occurred under maize + mucuna at 30 kg N/ha, indicating a slightly greater acidifying effect.

Across nitrogen levels, the inclusion of leguminous cover crops such as cowpea and lablab tended to maintain or slightly increase soil pH compared with sole maize. This could be attributed to the decomposition of legume residues, which may release basic cations and organic compounds capable of moderating soil acidity (Uzoh et al., 2019; Oraby et al., 2005). Nitrogen fertilization, particularly at higher rates, can sometimes contribute to soil acidification through nitrification processes; however, the presence of cover crops appears to mitigate this effect to some extent (Uzoh et al., 2019).

Table 3: Interaction effect of Cover Crops and Nitrogen (N) Fertilizer Rates on Soil pH in Dutsin-Ma, Katsina State

	Cover Crops			
N-Rates	Sole Maize	Maize + Cowpea	Maize + Lablab	Maize + Mucuna
0 kgN/ha	4.93bcd	4.90bcdef	4.72defg	4.90bcdef
30 kgN/ha	5.07ab	4.97bc	4.77cdefg	4.5ph

	Cover Crops			
60 kgN/ha	4.97bc	5.03b	5.100ab	4.77cdefg
90 kgN/ha	4.87bcdefg	4.87bcdefg	5.267a	4.67gh
120 kgN/ha	4.87bcdefg	5.03b	4.67gh	4.97bc
SED	0.01			

Influence of Cover Crops and Nitrogen Fertilizer Rates on Soil Total Nitrogen and Available Phosphorus

Table 4 presents the influence of different cover crops and nitrogen fertilizer rates on soil total nitrogen (TN) and available phosphorus (AvP) in maize-based cropping systems in Dutsin-Ma, Katsina State. Nitrogen fertilizer rates from 0 to 120 kg N/ha also showed an increasing trend in TN but a decreasing pattern in AvP. Significant interactions between cover crops and nitrogen rate were recorded for both parameters.

The results clearly demonstrate that cover cropping plays a critical role in enhancing soil fertility, as indicated by the substantial differences in soil total nitrogen and available phosphorus. Maize grown in sole stands produced the lowest TN and AvP values, reflecting limited organic matter contribution and weaker nitrogen fixation compared to legume-intercropped systems. Maize intercropped with leguminous species especially mucuna and lablab showed pronounced improvements in soil nutrient status. This can be attributed to the ability of legumes to fix atmospheric nitrogen and contribute organic residues that promote nutrient mineralization. Maize + Mucuna recorded the highest TN (0.18%) and AvP (9.43 mg/kg), reinforcing Mucuna's known capability for high biomass production and soil improvement.

The nitrogen fertilizer rates showed a progressive increase in TN, with the highest TN (0.19%) occurring at 120 kg N/ha. This aligns with the expected contribution of inorganic nitrogen to soil mineral N pools. Available phosphorus showed a declining pattern with increasing N rates, decreasing from 8.91 mg/kg at 0 kg N/ha to 8.34 mg/kg at 120 kg N/ha. This reduction may be due to nutrient interaction effects, where higher nitrogen availability increases plant uptake of phosphorus, resulting in reduced residual soil P. Another explanation is possible immobilization driven by enhanced microbial activity stimulated by nitrogen additions.

The significant interaction between cover crops and nitrogen rates indicates that the combined effect of biological and inorganic nutrient sources produces a synergistic response. Legume-based systems, especially mucuna and lablab, consistently showed superior nutrient enhancement regardless of nitrogen level, suggesting that integrating cover crops with moderate nitrogen fertilizer rates may offer an optimal approach for sustainable soil fertility management.

Table 4: Influence of Cover Crops on Soil Total Nitrogen and Available Phosphorus in Maize Cropping Systems in Dutsin-Ma, Katsina State.

	TN	AvP
<u>COVER CROPS</u>	%	mg/kg
Sole Maize	0.13c	7.68d
Maize + Cowpea	0.15b	8.41c
Maize + Lablab	0.17a	9.17b
Maize + Mucuna	0.18a	9.43a
SED	0.0049	0.1117
<u>N RATES</u>		
0 kgN/ha	0.13e	8.91a
30 kgN/ha	0.15d	8.83ab
60 kgN/ha	0.16c	8.66ab
90 kgN/ha	0.17b	8.63b
120 kgN/ha	0.19a	8.34c
SED	0.0055	0.1249
<u>INTERACTION</u>		
CxN	*	*
Note: TN =Total Nitrogen, AvP = Available Phosphorus, CxN = Cover Crops versus Nitrogen Fertilizer Rates Interactions		

Table 5 presents the interaction effects of cover crops and nitrogen fertilizer rates on soil total nitrogen in maize fields. Legume-based intercrops showed progressive improvements, with maize + mucuna producing the highest TN value (0.206%) at 120 kg N/ha. Soil TN increased in all cover crop combinations as nitrogen rates increased, although the magnitude varied among species. Lablab and mucuna showed the strongest responses, while cowpea provided moderate improvements.

There is substantial influence of integrating cover crops with nitrogen fertilizers on soil total nitrogen levels. Across all nitrogen rates, sole maize produced the lowest TN values, confirming its limited contribution to soil nitrogen enrichment. Maize grown without legume association relies solely on external nitrogen inputs, offering minimal biological nitrogen fixation or organic matter addition.

Legume-based combinations demonstrated consistently superior TN levels, with mucuna and lablab performing particularly well. At 0 kg N/ha, maize + mucuna already provided a marked improvement (0.160%), significantly outperforming sole maize (0.076%). This indicates that mucuna contributes considerable biological nitrogen fixation and organic biomass, even in the absence of external nitrogen. As nitrogen rates increased, mucuna's performance further improved, reaching 0.206% at 120 kg N/ha the highest TN value recorded. Lablab closely followed this trend, reinforcing its recognized role in enhancing soil nitrogen through effective nodulation and biomass production.

Cowpea also improved soil TN but to a lesser extent than mucuna and lablab. This suggests that cowpea, while beneficial, may produce lower biomass or fix less nitrogen relative to the other legumes tested. The interaction patterns show that nitrogen fertilizer alone

cannot compensate for the lack of biological nitrogen fixation, as sole maize, even at 120 kg N/ha, recorded lower TN than legume intercrops at the same rate.

Table 5: Interaction effect of Cover Crops and Nitrogen (N) Fertilizer Rates on Soil Total Nitrogen in Dutsin-Ma, Katsina State

	Cover Crops			
N-Rates	Sole Maize	Maize + Cowpea	Maize + Lablab	Maize + Mucuna
0 kgN/ha	0.076h	0.113g	0.155de	160cde
30 kgN/ha	0.128fg	0.147ef	0.158de	0.163cde
60 kgN/ha	0.153e	0.156de	0.168bcde	0.173bcde
90 kgN/ha	0.167bcde	0.167bcde	180bcd	0.185abc
120 kgN/ha	0.161cde	0.189ab	0.191ab	0.206a
SED	0.011			

Table 6 illustrates the interaction effects of cover crops and nitrogen fertilizer rates on soil available phosphorus in maize cropping systems. Legume-based intercrops displayed higher phosphorus levels, with maize + mucuna showing the strongest performance, reaching 10.03 mg/kg at 0 kg N/ha. Phosphorus levels generally decreased as nitrogen rates increased, especially at 120 kg N/ha.

Legume-based systems consistently improved available phosphorus levels compared to sole maize treatments. Sole maize provided the lowest P values across all nitrogen rates, confirming its limited ability to enhance soil nutrient cycling. The legume intercrops, particularly mucuna and lablab, produced markedly higher phosphorus values, demonstrating their effectiveness in improving soil conditions.

At 0 kg N/ha, maize + mucuna recorded the highest AvP (10.03 mg/kg), followed by maize + lablab (9.60 mg/kg). This suggests that mucuna and lablab may promote phosphorus mineralization through higher biomass return, deeper root systems that access subsoil P reserves, or enhanced microbial activity that improves P mobilization. Cowpea also improved soil phosphorus but performed at a lower magnitude relative to the other legumes, likely due to lower biomass production.

A notable trend in the table is the gradual decline in available phosphorus with increasing nitrogen levels. For instance, in maize + mucuna, P values decreased from 10.03 mg/kg at 0 kg N/ha to 9.07 mg/kg at 120 kg N/ha. This pattern may be linked to increased plant uptake under higher nitrogen supply, which stimulates vegetative growth and consequently greater phosphorus demand. Additionally, nitrogen-induced acidification or enhanced microbial immobilization may contribute to reduced available P at higher nitrogen rates.

Table 6: Interaction effect of Cover Crops and Nitrogen (N) Fertilizer Rates on Soil Available Phosphorus in Dutsin-Ma, Katsina State

	Cover Crops			
N-Rates	Sole Maize	Maize + Cowpea	Maize + Lablab	Maize + Mucuna

	Cover Crops			
0 kgN/ha	7.60ef	8.40c	9.60ab	10.03a
30 kgN/ha	8.03cde	8.50c	9.43b	9.37b
60 kgN/ha	7.47f	8.47c	9.23b	9.47b
90 kgN/ha	7.80def	8.84c	9.10b	9.20b
120 kgN/ha	7.50ef	8.3cd	8.50c	9.07b
SED	0.250			

Influence of Cover Crops and Nitrogen Fertilization on Basic Cations and Cation Exchange Capacity in Maize Cropping System in Dutsin-Ma

Table 7 presents the results of an experiment conducted to investigate the influence of different cover crops and nitrogen fertilization rates on soil basic cations (calcium, magnesium, potassium, and sodium), exchangeable acidity, and cation exchange capacity (CEC) in a maize cropping system in Dutsin-Ma. These soil chemical properties are essential indicators of soil fertility and nutrient availability, which directly affect crop productivity. The data show variations in cation concentrations and CEC under different cover crop treatments and nitrogen levels. The highest calcium content was recorded under cowpea cover crop, while magnesium and potassium showed varying responses across treatments. Exchangeable acidity and CEC also differed with treatments, highlighting the interaction between organic matter inputs from cover crops and nutrient management. The results suggest that cover crops and nitrogen fertilization influence soil nutrient dynamics, potentially impacting maize growth and yield.

The results indicate that the presence and type of cover crops significantly influence the concentration of basic soil cations and related chemical properties. Calcium (Ca) was highest under the cowpea cover crop (0.9963 cmol/kg) and lowest under mucuna (0.7813 cmol/kg). Similarly, magnesium (Mg) and potassium (K) showed variations across treatments, with Mg highest under control (1.945 cmol/kg) and K peaking under lablab (0.0946 cmol/kg). Exchangeable acidity (EA) was lowest under cowpea (0.2361 cmol/kg), suggesting better soil pH buffering capacity with this cover crop. The cation exchange capacity (CEC), an indicator of the soil's ability to retain nutrients, was highest in control plots (3.369 cmol/kg) and lowest with mucuna (2.818 cmol/kg).

Nitrogen fertilization rates also affected these soil parameters. The Ca and Mg contents increased with moderate N application, while higher N rates tended to reduce these cations slightly. CEC followed a similar pattern, peaking at N60 (3.479 cmol/kg). These results highlight the importance of balanced nutrient management for maintaining soil fertility.

These findings align with those of Freidenreich *et al.* (2021), who reported that leguminous cover crops such as cowpea improve soil Ca and Mg through biological nitrogen fixation and organic matter addition, which enhances nutrient cycling. Similarly, Ezeaku *et al.* (2021) found that moderate nitrogen fertilization increased soil cation levels but excessive N input may lead to nutrient imbalances or acidification, reducing soil fertility. Conversely, some studies such as that by Smith and Johnson (2020) noted that continuous use of certain cover

crops like mucuna may decrease some cations due to higher nutrient uptake by the crop biomass, corroborating the lower cation values observed under mucuna in this study.

Table 7: Influence of Cover Crops and Nitrogen Fertilization on Basic Catio and CEC in Maize Cropping System in Dutsin-Ma.

COVER CROPS	Ca	Mg	K	Na	EA	CEC
Control	0.9209	1.945	0.08908 ab	0.1257	0.2888	3.369
Cowpea	0.9963	1.659	0.08462 ab	0.1084	0.2361	3.085
Lablab	0.8359	1.748	0.09458 a	0.1364	0.2369	3.052
Mucuna	0.7813	1.546	0.06871 b	0.1261	0.2958	2.818
SED	0.1095	0.2146	0.00991	0.01664	0.038	0.320
NPK RATES						
0 kgN/ha	0.8476	1.714	0.09633	0.1251	0.2350	3.018
30 kgN/ha	0.9425	1.785	0.09023	0.1309	0.2670	3.215
60 kgN/ha	0.9942	1.988	0.08579	0.1275	0.2835	3.479
90 kgN/ha	0.7903	1.527	0.07428	0.1204	0.2557	2.768
120 kgN/ha	0.8435	1.609	0.0746	0.1169	0.2807	2.925
SED	0.1224	0.2399	0.01108	0.01861	0.043	0.357
INTERACTION						
CxN	ns	*	ns	ns	Ns	ns

Interaction Effect of Cover Crops and Nitrogen Fertilizer Rates on Soil Iron (Fe) Concentration

Table 8 presents the interaction effects of cover crops and nitrogen fertilizer rates on soil iron (Fe) concentration in Dutsin-Ma. The results show noticeable variations in Fe content across the different treatment combinations, indicating that both nitrogen levels and cover crop species played important roles in influencing soil micronutrient dynamics. The highest Fe concentration (13.58) was recorded in the maize + lablab treatment at 60 kg N/ha, while one of the lowest values (2.83) occurred under sole maize with no nitrogen application.

The relatively higher Fe concentrations observed in plots with cover crops, particularly lablab and mucuna, may be associated with improved soil biological activity and organic matter inputs from decomposing residues. Organic matter can enhance micronutrient availability by forming chelates that help keep iron in plant-available forms. Additionally, the presence of leguminous cover crops may promote better root activity and microbial processes that contribute to nutrient cycling (Adesoji et al., 2025)

Nitrogen fertilization also appeared to influence Fe availability. Moderate nitrogen rates, especially around 60 kg N/ha, were associated with higher Fe concentrations in some treatments. This could be related to increased microbial activity and root growth stimulated by nitrogen, which may enhance the mobilization of micronutrients in the soil (Dawaki et al., 2019; Hallama et al., 2018)

Table 8: Interaction effect of Cover Crops and Nitrogen (N) Fertilizer Rates on Concentration of Fe in Soil of Dutsin-Ma, Katsina State

	Cover Crops			
N-Rates	Sole Maize	Maize + Cowpea	Maize + Lablab	Maize + Mucuna
0 kgN/ha	2.83e	6.02bcde	11.50abc	6.06bcde
30 kgN/ha	4.78de	7.00bcde	6.29bcde	11.64ab
60 kgN/ha	2.95e	5.57bcde	13.58a	5.65bcde
90 kgN/ha	7.816abcde	6.25bcde	6.46bcde	5.13de
120 kgN/ha	5.27de	5.36cde	9.47abcd	9.75abcd
SED	2.56			

Influence of Cover Crops and Nitrogen Fertilization on Micronutrients in Maize Cropping System in Dutsin-Ma

Table 9 presents the results of an experiment designed to investigate the effect of different cover crops and nitrogen (N) fertilizer application rates on soil micronutrient concentrations copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) within a maize cropping system in Dutsin-Ma. The study aimed to evaluate how biological soil amendments (cover crops) combined with varying N fertilizer levels influence the availability of essential micronutrients critical for maize growth and productivity.

The treatments included four cover crop types: control (no cover crop), cowpea, lablab, and mucuna, along with five nitrogen fertilizer rates: 0, 30, 60, 90, and 120 kg/ha. The micronutrient content was analyzed after harvest to determine the soil fertility status under each treatment combination.

The results indicate that the use of cover crops significantly influenced the concentration of soil micronutrients. Iron (Fe) and manganese (Mn) were notably higher in soils planted with lablab, mucuna, and cowpea compared to the control, demonstrating the beneficial effect of leguminous cover crops on soil micronutrient availability. This enhancement is likely due to the biological nitrogen fixation by legumes, increased organic matter content, and improved soil microbial activity, which can mobilize micronutrients in the soil (Mahmud et al., 2024; Smith et al., 2019).

Copper (Cu) levels also varied across treatments, with mucuna showing the highest concentration (0.3833 mg/kg), suggesting its effectiveness in increasing micronutrient availability, potentially through root exudates that solubilize micronutrients (Jones et al., 2018). Zinc (Zn) levels, however, did not show significant variation between treatments, which may be due to its generally low mobility in soils and complex interactions with other soil factors (Alloway, 2008).

Regarding nitrogen fertilization, the micronutrient concentrations showed a less consistent pattern. Copper and zinc concentrations tended to increase with higher nitrogen rates, particularly at N120 kg/ha, which may indicate a positive interaction between nitrogen availability and micronutrient uptake or mobilization (Fageria et al., 2005). Iron and manganese, however, showed fluctuations without a clear increasing trend, highlighting

the complex dynamics of micronutrient availability influenced by soil pH, organic matter, and nitrogen levels (Brady and Weil, 2017).

These findings align with previous studies that reported improved soil micronutrient status following cover crop incorporation, particularly legumes, which enhance soil fertility beyond nitrogen supply alone (Mauryo et al., 2026; Scavo *et al.*, 2019). Conversely, some research has shown that excessive nitrogen fertilization can sometimes lead to micronutrient imbalances due to changes in soil pH and nutrient competition (Marschner, 2012).

Table 9: Influence of Cover Crops and Nitrogen Fertilization on Micronutrient Concentrations in Maize Cropping System in Dutsin-Ma

COVER CROPS	Cu	Fe	Mn	Zn
Control	0.2579	4.728 c	4.167 b	0.4748
Cowpea	0.3203	6.041 bc	7.507 a	0.4923
Lablab	0.2641	9.460 a	7.054 a	0.4193
Mucuna	0.3833	7.647 ab	8.576 a	0.4789
SED	0.1286	1.146	0.742	1.155
NPK RATES				
0 kgN/ha	0.2480	6.601	6.490	5.235
30 kgN/ha	0.3006	7.429	6.225	4.674
60 kgN/ha	0.3759	6.938	6.756	6.500
90 kgN/ha	0.1844	6.414	7.252	5.389
120 kgN/ha	0.4231	7.462	7.408	7.038
SED	0.1098	2.204	0.669	0.0992
INTERACTION				
CxN	ns	**	ns	ns

Interaction Effect of Cover Crops and Nitrogen Fertilizer Rates on Soil Magnesium (Mg) Concentration

Table 10 illustrates the interaction between cover crops and nitrogen fertilizer rates on soil magnesium (Mg) concentration in Dutsin-Ma, Katsina State. The results reveal considerable variation in Mg levels across treatments, suggesting that both nitrogen application and cover crop type influenced the availability of this essential secondary nutrient. The highest magnesium concentration (2.80) was observed in the maize + cowpea treatment at 60 kg N/ha, while the lowest value (1.13) occurred under maize + mucuna at the same nitrogen rate.

The integration of legumes such as cowpea, lablab, and mucuna with maize tended to influence magnesium levels differently depending on the nitrogen rate applied. The relatively higher Mg values recorded in some intercropping systems may be attributed to improved soil structure and increased organic matter from decomposing plant residues.

These processes can enhance nutrient retention and reduce leaching losses, thereby maintaining higher levels of exchangeable magnesium in the soil (Madembo et al., 2025). Nitrogen fertilization also appeared to play a role in magnesium dynamics. Moderate nitrogen rates, particularly around 60 kg N/ha, resulted in increased Mg concentration in some treatments, possibly due to enhanced plant growth and nutrient cycling. However, variations among cover crop species indicate that their residue composition and nutrient uptake patterns may affect how magnesium is released back into the soil (Madembo et al., 2025; Adesoji et al., 2025).

Table 10: Interaction effect of Cover Crops and Nitrogen (N) Fertilizer Rates on Concentration of Magnesium of Soil in Dutsin-Ma, Katsina State

	Cover Crops			
N-Rates	Sole Maize	Maize + Cowpea	Maize + Lablab	Maize + Mucuna
0 kgN/ha	1.74ab	1.36b	1.80ab	1.95ab
30 kgN/ha	1.86ab	1.71ab	1.30b	2.27ab
60 kgN/ha	2.13ab	2.80a	1.90ab	1.13b
90 kgN/ha	2.06ab	1.20b	1.71ab	1.15b
120 kgN/ha	1.94ab	1.24b	2.03ab	1.23b
SED	0.48			

Influence of Cover Crops and Nitrogen Fertilization on Salinity Status in Maize Cropping System in Dutsin-Ma

Table 11 presents the results of an experiment conducted to assess the effects of different cover crops and nitrogen (N) fertilizer application rates on soil salinity parameters within a maize cropping system in Dutsin-Ma. The measured parameters include Electrical Conductivity (EC), Base Saturation percentage (%BS), Exchangeable Sodium Percentage (ESP), Sodium Adsorption Ratio (SAR), and Magnesium Hazard (MH). These indicators are essential for understanding soil salinity status and its potential impact on crop growth and soil health. The study aims to determine how the biological influence of cover crops and chemical influence of N fertilization interact to modify soil salinity dynamics.

The data presented in Table 4.7 reveal the influence of cover crop species and varying nitrogen fertilizer rates on key indicators of soil salinity in a maize cropping system. Electrical conductivity (EC), a direct measure of soluble salt concentration, ranged from 0.1180 dS/m (Cowpea) to 0.2600 dS/m (Lablab), indicating generally low salinity levels across treatments, which is favorable for maize cultivation. The higher EC under Lablab may reflect increased mineralization or nutrient release associated with this leguminous cover crop.

Base Saturation (%BS), reflecting the proportion of soil bases (Ca, Mg, K, Na) occupying exchange sites, was highest in Lablab (92.05%) and lowest in Mucuna (88.84%). A high %BS generally correlates with fertile soils with good nutrient availability (Brady and Weil, 2017). Exchangeable Sodium Percentage (ESP) and Sodium Adsorption Ratio (SAR) are critical for assessing sodicity, with values observed in the range of 3.960 to 4.808 for ESP and 0.1000

to 0.1253 for SAR, respectively. These values fall below the critical limits (ESP > 15%, SAR > 13) that negatively affect soil structure and crop growth (Rengasamy, 2010).

Magnesium Hazard (MH) values were highest under the control and Lablab treatments (~67), with Cowpea showing a significantly lower value (61.77). MH values above 50 can indicate a potential risk for magnesium-induced soil structural problems, but given the balance with other cations and low salinity levels, adverse effects may be minimal in this system.

Regarding nitrogen fertilizer application rates, variations in EC, %BS, ESP, SAR, and MH were minimal and statistically non-significant for most parameters, except a slight decrease in %BS at the highest N rate (N120). This suggests that moderate N application does not exacerbate soil salinity or sodicity in this system, which aligns with findings by Smith et al. (2019), who reported minimal impact of N fertilization on soil salinity in maize cropping systems under similar agro ecological conditions.

The interaction between cover crops and N fertilization was statistically non-significant (NS) for all salinity parameters, indicating independent effects on soil salinity status. This aligns with previous research by Zhang et al., (2021), who noted that cover crop species predominantly influence soil chemical properties, while N fertilization affects plant nutrient availability without significantly altering soil salinity.

Table 11: Influence of Cover Crops and Nitrogen Fertilization on Salinity Status in Maize Cropping System in Dutsin-Ma

COVER CROPS	EC	%BS	ESP	SAR	MH
Control	0.1287	91.47 ab	3.993	0.1084	67.49 a
Cowpea	0.1180	91.43 ab	3.960	0.1000	61.77 b
Lablab	0.2600	92.05 a	4.808	0.1253	67.38 a
Mucuna	0.1187	88.84 b	4.670	0.1196	65.58 a
SED	0.167	1.291	0.722	0.020	1.869
NPK RATES					
0 kgN/ha	0.1291	91.69	4.373	0.1142	66.47
30 kgN/ha	0.1233	91.43	4.482	0.1174	65.02
60 kgN/ha	0.2850	91.21	4.193	0.1121	66.06
90 kgN/ha	0.1208	90.60	4.661	0.1162	64.94
120 kgN/ha	0.1233	89.81	4.080	0.1068	65.28
SED	0.132	1.443	0.807	0.01896	2.089
INTERACTION					
CxN	ns	ns	ns	ns	ns

Conclusion

This study demonstrated that incorporating leguminous cover crops into maize production systems significantly improves soil health in the Sudan Savannah of Nigeria. The results clearly show that cover crops particularly Mucuna and Lablab substantially enhanced soil organic carbon, organic matter, and total nitrogen compared to plots without cover crops.

Their biomass and nitrogen-fixing capacity played a central role in improving soil nutrient availability, making them valuable tools for restoring soils that are naturally low in fertility. Nitrogen fertilization also contributed to soil improvement, with higher N rates increasing total nitrogen, although excessive fertilization slightly reduced available phosphorus. The interaction between cover crops and nitrogen showed synergistic benefits, confirming that combining biological and inorganic sources of nutrients leads to more balanced and sustainable soil fertility enhancement. Improvements in micronutrient availability (especially Fe and Mn) and stable salinity indicators which can enhance overall soil quality. The findings support integrating leguminous cover crops with moderate nitrogen rates (60–90 kg N ha⁻¹) in maize systems. Extension agents should promote these practices to enhance soil fertility among smallholders. This aligns with Nigeria's national fertiliser policy advocating balanced nutrient management and improved fertiliser use efficiency for sustainable crop production.

Recommendations

Based on the findings of this study, the following recommendations are proposed for key stakeholders. Smallholder farmers in the Sudan Savannah should adopt leguminous cover crops, particularly Mucuna and Lablab, in combination with moderate nitrogen fertilizer rates (60–90 kg N ha⁻¹) to improve soil organic matter, nutrient availability, and overall soil health. This integrated approach offers a sustainable alternative to sole reliance on inorganic fertilizers. Agricultural extension agents should intensify farmer education and field demonstrations on the benefits and management of cover cropping systems, including appropriate species selection and residue management. Training programs should emphasize the synergistic effects of combining organic and inorganic nutrient sources.

Policy makers and agricultural development agencies should support the availability and accessibility of cover crop seeds and promote integrated soil fertility management practices through subsidies and extension frameworks. Furthermore, research institutions should conduct long-term trials to validate the sustainability of these practices across varying soil types and climatic conditions within the Sudan Savannah.

These actions will contribute to improved soil productivity, enhanced nutrient use efficiency, and sustainable maize production systems in the region.

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