Selcuk Journal of Agriculture and Food Sciences

https://dergipark.org.tr/tr/pub/selcukjafsci

Research Article

(2025) 39(3), 649-657 DOI:10.15316/selcukjafsci.1613142 e-ISSN: 2458-8377 Selcuk J Agr Food Sci

Phosphorus Forms and Distribution in Soils: A Comparative Study of Different Land Use Types

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HIGHLIGHTS

- Forest soils showed the highest available phosphorus (10.92 mg/kg).
- Cultivated soils had the lowest phosphorus concentration (8.97 mg/kg).
- Phosphorus forms declined with soil depth across all land uses.
- Iron-bound phosphorus (Fe-P) dominated the inorganic phosphorus fraction.

Abstract

Phosphorus (P) is a critical macronutrient for plant and microorganism development, playing a vital role in energy transmission, cell structure, biomass accumulation, and primary productivity. However, its low availability in tropical and subtropical soils often limits agricultural output. This study investigated phosphorus forms and distribution in soils: a comparative study of different land use types in Anyigba, Kogi State University area. Twenty-four soil samples were collected from four land uses (forest, cultivated, fallow, and built-up areas) at two depths (0-15 cm and 15-30 cm). The study employed a 4 × 3 × 2 factorial experiment in a Randomized Complete Block Design. Soil analyses revealed low levels of available P, with the highest concentration found in forest land (10.92 mg/kg) and the lowest in cultivated land (8.97 mg/kg). Phosphorus forms declined with depth, and iron-bound phosphorus (Fe-P) was the dominant inorganic phosphorus fraction. The results suggest that continuous crop cultivation leads to lower organic matter content and phosphorus concentrations in cultivated soils. This study highlights the importance of phosphorus fraction investigations in cultivated soils to inform fertilizer recommendations and boost productivity.

Keywords: Land Use Types; Soil Depths; Phosphorus Fractions; Forest Ecosystems; Cultivated Ecosystems

Citation: Jayeola, O. E., Efenudu, I. U., & Dayo-Olagbende, G. O. (2025). Phosphorus Forms and Distribution in Soils: A Comparative Study of Different Land Use Types. *Selcuk Journal of Agriculture and Food Sciences*, 39(3), 649-657. https://doi.org/10.15316/selcukjafsci.1613142

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Received date: 04/01/2025

Accepted date: 30/11/2025

1. Introduction

After nitrogen (N), phosphorus (P) stands as the second most critical macronutrient for both plant and microorganism development (Mou et al. 2020). Found in nucleic acids, phospholipids, and ATP, phosphorus plays vital roles in energy transmission and cell structure. Moreover, it is indispensable for biomass accumulation and primary productivity (Turner et al. 2018). However, in the heavily weathered soils of tropical and subtropical regions, phosphorus often exists in forms with low availability, posing a significant limitation to agricultural output (Osodeke 2005; Rowe et al. 2016). Despite soil phosphorus content typically exceeding plant requirements, its limited mobility and high fixation can constrain its availability and biological utilization by plants (Cessa et al. 2009; Yi-Halla 2016; Umoh et al. 2019). Phosphorus exists in soil in two primary forms: organic and inorganic (Busman et al. 2002). Organic forms, including nucleic acids, nucleotides, inositol, phospholipids, and sugar phosphates, account for 20–80 % of total phosphorus (Mustapha et al. 2007; Uzoho 2010). Meanwhile, inorganic phosphate fractions such as iron-phosphate bound (Fe-P), aluminum-phosphate bound (Al-P), calcium phosphate bound (Ca-P), reductant phosphorus (Red-P), saloid-bound P, and residual P play crucial roles in regulating soil phosphorus availability and losses through processes like uptake, leaching, and erosion (Azadi and Baghernejad 2016). Its distribution varies depending on land use and composition in both natural and agro-ecosystems (Aguiar et al. 2013). In tropical soils, organic phosphorus plays a crucial role due to the high acidity and concentration of iron (Fe) and aluminum (Al) sesquioxides, which promote phosphorus absorption and chemical fixation in non-labile fractions (Gama-Rodrigues et al. 2014). In the absence of phosphorus addition, the turnover of organic phosphorus and rapid recycling of phosphorus from litter fall are the primary mechanisms driving phosphorus availability to plants in natural environments (Johnson et al. 2013). Phosphorus deficiency results in poor root formation, slow growth, inadequate seed set, and reduced fruit output, all contributing to decreased agricultural yields (Brady and Weil 2008; Khan et a*l.* 2013). One of the most influential factors affecting the physical, chemical, and biological properties of soil is land use change, which modifies vegetation cover and other associated characteristics (Geissen et al. 2009; Tellen and Yerima 2018). Notably, land use changes have affected the condition and distribution of soil phosphorus (Chacon and Dezzeo 2004; McDowell and Stewart 2006). For instance, studies have revealed that land use change significantly impacts phosphorus availability for plant uptake, either by increasing phosphorus losses or transforming it into more recalcitrant forms (Maranguit et al. 2017). Despite the development of various methodologies to investigate the diverse phosphorus pools in soil and their responses to land use and soil management (Gatiboni et al._2021), comprehensive studies revealing the impact of land use on soil P fractions are still scarce particularly in the Guinea savanna region of Nigeria like Kogi state. Phosphorus (P) is crucial to research because there is no substitute for it in plant growth. Phosphorus cannot exist on its own; it must mix with other elements to produce phosphate, which limits the amount of accessible phosphorus (P) in the soil. Understanding the trend or status of P availability in different land use types at Kogi State University in Anyigba, Nigeria will ensure optimal study management in terms of available phosphorus (P).

2. Materials and Methods

2.1. Site description

The investigation was done on the Kogi State University campus. Anyigba is one of numerous settlements in Kogi's Dekina Local Government Area. It is located in Nigeria's derived Guniea Savannah zone. Anyigba is located between latitude 7°29'N and longitude 7°11'E, 385 metres above sea level, with a total land mass size of 420 square kilometres and an estimated population of 187,976 people (Ifatimehin et al. 2012). Kogi state has an estimated population of 2,141,756 people (Ali et al. 2012). The climate is generally humid tropical with two distinct seasons: rainy and dry. Kogi State experiences a distinct rainy season, which typically commences in April, reaches its peak in July, and concludes in September, with a brief hiatus in August. The dry season, on the other hand, spans from September to April of the following year. The region receives an average annual rainfall of 1260 mm (Amhakhian et al. 2006). The temperature in Kogi State remains relatively consistent throughout the year, ranging from 27 °C to 38 °C (Audu 2001). This study focused on four distinct land-use types, namely: Cultivated land (CL), Forest land (FL), Grassland (GL), and Plantation land (PL). These land-use types were selected to investigate their impact on soil characteristics and other environmental factors.

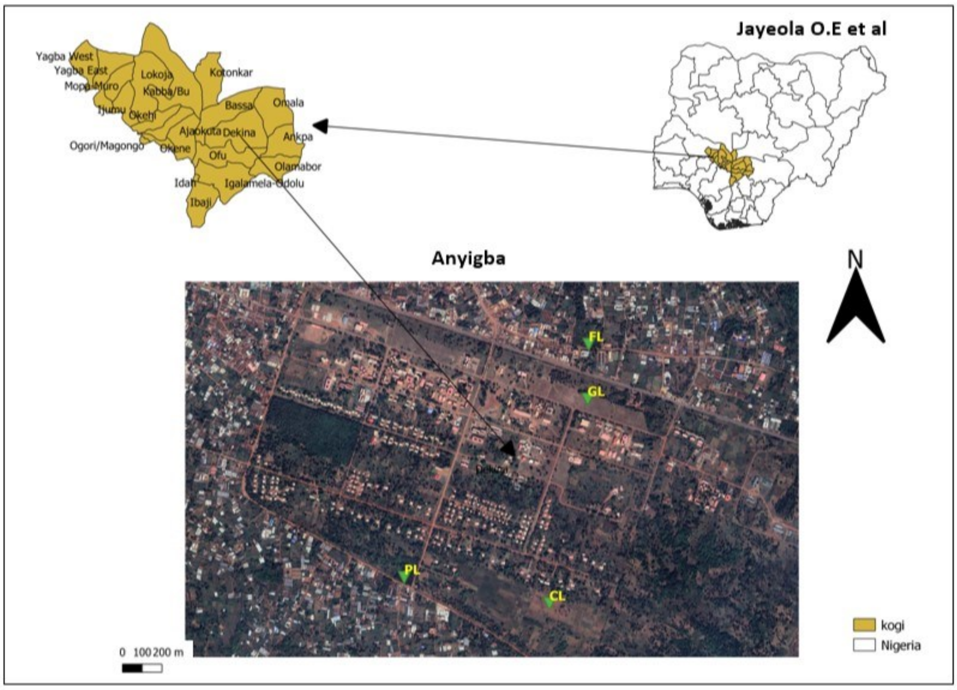

Figure 1. A satellite photograph of Kogi State University's Teaching and Research Farm in Anyigba. Nigeria's Kogi State. Displaying the four land-use types that have been selected. CL stands for cultivated land use, FL for forest land use, GL for grassland use, and PL for plantation land use.

2.2. Soil sampling and preparation

A total of 24 soil samples were collected from the vegetative zone of the Anyigba University in Kogi state, Nigeria. Land use was classified into four types: cultivated land, forest land, grassland, and plantation land. At each site, five soil samples were collected at random from depths ranging from 0 to 15 cm and 15 to 30 cm with the use of a soil auger, the sampling sites were combined (bulked) to create a sample at the 0-15 cm and 15-30 cm soil depth layers. All soil samples were air-dried at a constant room temperature, then crushed and sieved through a 2 mm sieve to reduce coarseness. The phosphorus forms of the soil samples were examined at Kogi State University's Soil Laboratory in Anyigba.

2.3. Phosphorus forms and distribution analysis

Available phosphorus was determined using Bray's No. 1 method (Bray and Kurtz 1945), which involves an HCl: NH4F mixture. The phosphorus content of the extract was then measured using a Spectronic 21D spectrophotometer and the blue ammonium molybdate procedure, with ascorbic acid as the reducing agent (Rodriguez et al. 1994). Inorganic and organic phosphorus fractions were sequentially fractionated using the method described by Udo et al. (2009). Organic phosphorus was calculated as the difference in extractable inorganic phosphorus before and after ignition, based on the method of Legg and Black (1955).

2.4. Statistical analysis

The findings were gathered through soil observations and laboratory tests. All soil samples data were subjected to Analysis of Variance (ANOVA) using the Minitab statistical programme. The means were separated using Turkey's test at a significance level of 5 %.

3. Results

3.1. Effects of land use on soil phosphorus forms and distribution

The results presented in Table 1 demonstrate the impact of land use on phosphorus forms and distributions in Anyigba, Kogi State, Nigeria. A significant variation in available phosphorus (available-P) was observed among different land use types, with the overall mean values following the order: Forest Land (FL) > Grassland (GL) > Plantation Land (PL) > Cultivated Land (CL).

The total organic phosphorus (organic-P) content varied substantially across land use types, depending on the parent material. The highest organic-P content was found in forest land (1452.92 mg/kg), while the lowest was recorded in cultivated land (1033.48 mg/kg). Furthermore, the total inorganic phosphorus (inorganic-P) content was highest in forest soil at depths of 0-15 cm, with a value of 674.15 mg/kg. The distribution and amount of inorganic-P components differed significantly among land use types (Table 1). Iron-bound phosphorus (Fe-P) was the most abundant inorganic-P component across all land use systems, followed by aluminum-bound phosphorus (Al-P) and calcium-bound phosphorus (Ca-P). Plantation land had the highest Fe-P and Ca-P concentrations, while forest land had the highest Al-P content. Notably, high levels of Fe-P, Ca-P, and Al-P were found in plantation and forest land soils, respectively. The reductant available phosphorus (Red-P) ranged from 86.82 mg/kg to 116.50 mg/kg, following a trend similar to that of Fe-P and Ca-P. The highest Red-P value was observed in plantation land, while the lowest was recorded in grassland soils. Finally, the occluded Fe-Al phosphorus (occ/Fe-Al-P) concentrations in the study area ranged from 54.53 mg/kg to 76.08 mg/kg. The highest occ/Fe-Al-P value was found in forest land, while the lowest was observed in cultivated land.

Table 1. Effect of land use on forms and distribution of phosphorus in Anyigba Kogi state, Nigeria.

Land use	AVP (mg/kg)	Total-Po (mg/kg)	Total-Pi (mg/kg)	Ca-P (mg/kg)	Fe-P (mg/kg)	Red-P (mg/kg)	Al-P (mg/kg)	Occ/Fe-Al-P (mg/kg)
CL	8.97d	1033.48d	539.93b	9.41c	226.75d	99.93c	164.90c	54.53d
FL	10.92a	1452.92a	609.70a	10.48b	238.46b	104.21b	177.72a	76.08a
GL	9.70b	1122.10c	523.93b	9.71c	234.68c	86.82d	166.03bc	60.87c
PL	9.63c	1354.63b	628.58a	12.98a	264.00a	116.50a	167.93b	67.07b

Tukey's Test at $p \leq 0.05$ shows that means followed by the same letter are not significantly different from one another.

3.2. Effects of land use on soil phosphorus forms and distribution of phosphorus

Table 2 indicates how depths of 0-15 cm and 15-30 cm affect the phosphorus forms and distribution, respectively. Significant differences were found between treatments based on the mean values. The phosphorus forms decrease with depth; according to the data in the table, depth 0-15 cm had the greatest levels for all soil phosphorus forms.

3.3. Interaction effects of Land use types by depths on soil phosphorus forms and distribution

The available phosphorus content in Anyigba soils exhibited significant variability, as shown in Table 3. This study revealed a significant relationship ($p<0.05$) between soil depth and land use type on phosphorus forms and distribution. Available phosphorus (P) concentrations ranged from 7.47 mg/kg to 11.53 mg/kg and decreased with increasing soil depth across all land use types. In contrast, calcium-bound phosphorus (Ca-P) content varied by land use, with values ranging from 8.23-10.58 mg/kg, 9.45-11.52 mg/kg, 9.03-10.38 mg/kg, and 12.52-13.45 mg/kg. Interestingly, Ca-P content increased with depth in all land use types, except for forest land, where it decreased with depth. Iron-bound phosphorus (Fe-P) was the dominant form of inorganic phosphorus across all four land use types, with concentrations ranging from 192.35-261.15 mg/kg, 204.48-272.43 mg/kg, 200.58-268.78 mg/kg, and 258.92-269.09 mg/kg in cultivated land, forest land, grassland, and plantation land, respectively. In contrast, aluminum-bound phosphorus (Al-P) concentrations decreased with depth across all land use types, with forest land exhibiting the highest values. Similarly, reductant available phosphorus (Red-P) followed the same trend as Al-P, with maximum concentrations found in soils beneath forest land. Notably, occluded iron-aluminum phosphorus (Occ/Fe-Al-P) was relatively abundant compared to Fe-P, Al-P, and Red-P. As shown in Table 3, Red-P concentrations were higher at surface depths and decreased with increasing depth across all four land use types.

Table 2. Effect of land use on forms and distribution of phosphorus.

Depths (cm)	AVP (mg/kg)	Total-Po (mg/kg)	Total-Pi (mg/kg)	Ca-P (mg/kg)	Fe-P (mg/kg)	Red-P (mg/kg)	Al-P (mg/kg)	Occ/Fe-Al-P (mg/kg)
0-15	10.96a	1359.06a	639.98a	10.97a	267.86a	112.22a	180.18a	70.31a
15-30	8.40b	1122.51b	511.09b	10.33b	214.08b	91.51b	158.11b	58.97b

Mean with the same letter in superscript on a column for same parameter are not different ($p<0.05$) from one another based on Tukey's test.

Table 3. Interaction effect of Land use by depths on forms and distribution of phosphorus.

Land use	Depths (cm)	AVP (mg/kg)	Total-Po (mg/kg)	Total-Pi (mg/kg)	Ca-P (mg/kg)	Fe-P (mg/kg)	Red-P (mg/kg)	Al-P (mg/kg)	Occ/Fe-Al-P (mg/kg)
CL	0-15	10.34ab	1186.60f	612.38b	8.23f	261.15b	106.22c	179.55b	57.25e
	15-30	8.61cd	880.37h	467.48d	10.58cd	192.35e	93.65d	150.25e	51.82f
FL	0-15	10.62a	1537.50a	674.15a	11.52bc	272.43a	113.03b	189.78a	89.92a
	15-30	8.55cd	1368.33c	545.25c	9.45de	204.48c	95.38d	165.65d	62.25cd
GL	0-15	11.35a	1261.33d	630.35ab	9.03ef	268.78a	110.32bc	180.95b	62.35cd
	15-30	7.47d	982.87g	417.50d	10.38cd	200.58d	63.32e	151.12e	59.38de
PL	0-15	11.53a	1450.80b	643.03ab	12.52ab	269.09a	119.32a	170.45c	71.72b
	15-30	8.97bc	1258.47e	614.13ab	13.45a	258.92b	113.68ab	165.42d	62.42c

Mean with the same letter in superscript on a column for same parameter are not different ($p<0.05$) from one another based on Tukey's test.

Table 4. Summary of the interaction effects of Land use by depths on soil phosphorus forms and distribution.

Land use	AVP (mg/kg)	Total-Po (mg/kg)	Total-Pi (mg/kg)	Ca-P (mg/kg)	Fe-P (mg/kg)	Red-P (mg/kg)	Al-P (mg/kg)	Occ/Fe-Al-P (mg/kg)
CL	8.97d	1033.48d	539.93b	9.41c	226.75d	99.93c	164.90c	54.53d
FL	10.92a	1452.92a	609.70a	10.48b	238.46b	104.21b	177.72a	76.08a
GL	9.70b	1122.10c	523.93b	9.71c	234.68c	86.82d	166.03bc	60.87c
PL	9.63c	1354.63b	628.58a	12.98a	264.00a	116.50a	167.93b	67.07b
Depths								
0-15 cm	10.96a	1359.06a	639.98a	10.97a	267.86a	112.22a	180.18a	70.31a
15-30 cm	8.40b	1122.51b	511.09b	10.33b	214.08b	91.51b	158.11b	58.97b
Three-way ANOVA								
Land use	*	*	*	*	*	*	*	*
Depths	*	*	*	*	*	*	*	*
Land use × Depth	*	*	*	*	*	*	*	*

Mean with the same letter in superscript on a column for same parameter are not different ($p<0.05$) from one another based on Tukey's test * $p < 0.05$.

Table 5. Correlation Coefficient among soil phosphorus forms and distribution.

	AVP (mg/kg)	Total-Po (mg/kg)	Total-Pi (mg/kg)	Ca-P (mg/kg)	Fe-P (mg/kg)	Red-P (mg/kg)	Al-P (mg/kg)	Occ/Fe-Al-P (mg/kg)
AVP	1.00							
Total-Po	0.70*	1.00						
Total-Pi	0.88*	0.80*	1.00					
Ca-P	0.27	0.32	0.29*	1.00				
Fe-P	0.88*	0.71*	0.92*	0.29	1.00			
Red-P	0.71*	0.79*	0.86*	-0.10	0.83*	1.00		
Al-P	0.82*	0.67*	0.93*	0.38	0.78*	0.65*	1.00	
Occ/Fe-Al-P	0.55*	0.84*	0.64*	0.42	0.59*	0.67*	0.44	1.00

The star (*) indicates that correlation is significant at $p<0.05$ level

3.4. Correlation Coefficient among soil phosphorus forms and distribution

Table 4 reveals the relationships among various phosphorus forms. The results show that total organic phosphorus (organic-P) is strongly and positively correlated with available phosphorus (available-P). Total inorganic phosphorus (inorganic-P) exhibited a significant positive correlation with available-P (r = 0.88) and organic-P (r = 0.80*). Iron-bound phosphorus (Fe-P) also showed substantial positive correlations with available-P (r = 0.88*), organic-P (r = 0.71*), and inorganic-P (r = 0.92*). Similarly, aluminum-bound phosphorus (Al-P) was significantly positively correlated with available-P, organic-P, inorganic-P, and Fe-P. However, Al-P was non-significantly negatively correlated with calcium-bound phosphorus (Ca-P) (r = -0.10). Reductant available phosphorus (Red-P) exhibited substantial positive correlations with available-P (r = 0.82*), organic-P (r = 0.67*), inorganic-P (r = 0.93*), Fe-P (r = 0.78*), and Al-P (r = 0.65*). However, Red-P was not significantly correlated with Ca-P (r = 0.38). Occluded iron-aluminum phosphorus (Occluded/Fe-Al-P) showed significant positive correlations with available-P, organic-P, and inorganic-P (r = 0.55*, 0.84*, 0.64*, 0.59*, and 0.67*). However, Occluded/Fe-Al-P was not significantly correlated with Ca-P and Red-P (r = 0.42 and 0.44).

4. Discussion

The table results showed that there were considerable variances in phosphorus forms among the specified land use types. According to the results shown in (Table 3), available-P ranged from 7.47 mg/kg to 11.53 mg/kg and decreased with soil depth in each land use. The low content detected in the subsoil layers (15-30 cm) across the four land use categories could be attributed to the declining trend of organic carbon in the depths. This is consistent with the findings of Trivedi et al. (2010). This difference could be attributed to the use of phosphorous fertilizer as part of the periodic maintenance of cultivated land. Based on the essential threshold of 15 mg/kg, all soils in the land-use system were phosphorus deficient. As a result, available phosphorus in the examined area was typically low in P, notably on Kogi state university farm, showing Kogi state university farm's poor phosphorus fertility status of Anyigba soil. The decrease in available phosphorus in other land use types may be due to fixation and erosion (Njoku 2019). As shown in Table 1, total organic-P content in land use varied greatly depending on the parent material, with the highest measured in forest land (1452.92 mg/kg) and the lowest in cultivated land (1033.48 mg/kg). The high concentration of total organic-P in the forest area could be related to the presence of high organic matter in the soil (Adegbenro et al. 2011). Forest soil at depths of 0-15 cm had the highest total inorganic-P content (674.15 mg/kg). The amount and distribution of inorganic-P components differed considerably among land use types (table 1). According to the data in (Table 3), the Ca-P content in the four-land use content ranged from 8.23 to 10.58 mg/kg, 9.45 to 11.52 mg/kg, 9.03 to 10.38 mg/kg, and 12.52 to 13.45 mg/kg respectively. Across all land use systems, Ca-P content increases with depth, with the exception of forest land, where it decreases. Ca-P concentrations were low in most land uses. The soil's low Ca-P composition suggests a higher degree of weathering (Omorege et al. 1999). Fe-P content was higher than Al-P and other types of inorganic phosphorus across all four land uses. Fe-P concentrations varied from 192.35 to 261.15 mg/kg, 204.48 to 272.43 mg/kg, 200.58 to 268.78 mg/kg, and 258.92 to 269.09 mg/kg in cultivated land, forest land, grassland, and plantation land, respectively. The high Fe-P content could be attributed to the soil's pH, which ranges from very strongly to strongly acidic, as well as the abundance of Fe in soils produced on parent materials. Adegbenro et al. (2011) found a high Fe-P compared to other forms of P. The abundance of Fe-P among active inorganic P was comparable with the results of Asmare et al. (2015). Similarly, the Al-P content of soils decreased with depths across all four land use groups, with forest land having the highest value. The reductant available phosphorus (Red-P) follows the same trend as the Al-P, with the highest concentrations seen in soils under forest land. The occluded iron-aluminum phosphorus (Occ/Fe-Al-P) is fairly rich when compared to Fe-P, Al-P, and reductant available phosphorus. As shown in table 3, red-P phosphorus was higher at surface depths and reduced as depth increased in all four land use types. This is consistent with the report by Trivedi et al. (2010).

5. Conclusions

This paper investigated the impact of land use types on soil P fractions in the Guinea savannah ecosystem of Anyigba Kogi State, North Central Nigeria. Our findings revealed that soil P fractions declined significantly at depths following land use change. Higher P fractions were found at depths ranging from 0 to 15 cm. The results showed that, available-P of the soils is generally low because it does not measured up to the phosphorus ratings of 12 to 18 mg/kg, which are considered adequate for optimum crop growth, so the available phosphorus of cultivated, forest, field, and plantation soils, particularly that of Kogi State University farm (cultivated land) of Anyigba were not sufficient. However, among all the soil types, forestland (FL) showed the highest for most of the P fractions. Available-P, total Po, total Pi, Al-P and Occ/Fe-Al-P were highest in FL soils after forest conversion, due to farmers having used P fertilizer on their land to increase crop production. Generally, this study confirmed that land use change had a significant impact on the contents of P fractions in Kogi State University soils, Anyigba. These findings could have substantial implications for soil P management to maintain soil P reserves by reducing the loss of SOM.

Author Contributions: All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the Concept, Design, Data Collection or Processing, Statistical Analyses, Literature Search, Writing, Review and Editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors acknowledge the technical assistance of the technologists in the Soil Science Section of the Department of Soil and Environmental Management, Kogi State University Anyigba, Nigeria for their assistance rendered with soil analysis and laboratory work.

Conflicts of Interest: There is no conflict of interest between the article authors. We sought the permission of the university farm management, Kogi State University before sampling. We declare that there is no conflict of interest between us as the article authors.

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