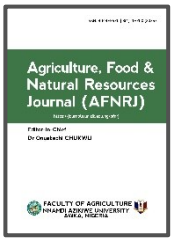
Agr. Foo. Nat. Res. J. Volume 5, Issue 2, Page: 1- 7

e-ISSN: 1597-7153 | p-ISSN: 3043-5420

Agriculture, Food and Natural Resources Journal

The Official Journal of the Faculty of Agriculture, Nnamdi Azikiwe University, Awka, Nigeria

Journal homepage: https://journals.unizik.edu.ng/afnrj



Original Article

Effects of parkland agroforestry on soil fertility indices in northern Katsina State, Nigeria

OPEN ACCESS

Badiatu Sade ABDULLAHI*, Sulaiman Sani KANKARA, Nasiru Hassan WAGINI & Usman Lawal USMAN

Department of Biological Sciences, Faculty of Natural and Applied Sciences, Umaru Musa Yar'adua University, Katsina, Nigeria

DOI: https://doi.org/10.5281/zenodo.22976228

Editor: *Onyekachi Chukwu, Nnamdi Azikiwe University, NIGERIA*

Received: *July 28, 2025*
Accepted: *August 26, 2026*
Available online: *September 30, 2026*

Peer-review: *Externally peer-reviewed*

Copyright: © 2026 Author(s)
This is an open access article licensed under Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/) which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Conflict of Interest: *The authors have no conflicts of interest to declare*

Financial Disclosure: *The authors declared that this study has received no financial support.*

ABSTRACT

Agroforestry is widely recognized as a sustainable land-use system that improves soil fertility and ecosystem resilience, particularly in semi-arid environments. This study evaluated the influence of parkland agroforestry on selected soil fertility indicators in Northern Katsina State, Nigeria. Twenty-four composite soil samples (0–20 cm) were collected from parkland agroforestry systems and adjacent open farmlands in Dutsi, Daura, Baure and Kankia Local Government Areas. Soil pH, organic carbon, organic matter, total nitrogen, available phosphorus and exchangeable potassium were analyzed using standard procedures. A Soil Fertility Index (SFI) was computed from standardized soil variables. Data were analyzed using descriptive statistics, Analysis of Variance and Tukey–Kramer post hoc tests, with statistical significance assessed at $\alpha = 0.05$. Significant differences were observed among the location × land-use groups for all measured soil fertility indicators ($p < 0.0001$), with parkland systems generally recording higher values than adjacent open farmlands. The mean SFI was higher under parkland systems (0.57 ± 0.74) than open farmlands (-0.57 ± 0.43). These findings demonstrated that parkland agroforestry was associated with higher soil fertility, based on the measured soil fertility indicators and Soil Fertility Index. Promoting the retention and integration of indigenous trees in farmlands may therefore contribute to sustainable soil management in semi-arid northern Nigeria.

KEYWORDS: *Nutrient cycling, Soil physicochemical properties, Semi-arid, Tree crop interaction.*

INTRODUCTION

Soil fertility is a key determinant of agricultural productivity and ecosystem sustainability because it regulates nutrient availability, soil biological activity, moisture retention and plant growth. However, maintaining soil fertility remains a major challenge in the semi-arid regions of sub-Saharan Africa due to low and erratic rainfall, continuous cultivation, deforestation, overgrazing and unsustainable land-use practices. These factors accelerate soil degradation, reduce soil organic matter, and diminish nutrient availability, resulting in declining crop yields and increasing food insecurity (Lal, 2020; FAO, 2021; Mpongwana *et al*, 2024; Ayeni *et al*., 2025; Onokebhagbe *et al*., 2025; Mogale *et al*., 2026).

Agroforestry has been widely recognized as a sustainable land-use system that enhances soil fertility while improving biodiversity conservation, carbon sequestration and climate resilience (Sekhar *et al*., 2023; Kugedera *et al*., 2025). The integration of trees with crops promotes nutrient cycling through litter decomposition, root turnover, biological nitrogen fixation, and the redistribution of nutrients from deeper soil layers to the surface. Consequently, agroforestry systems generally maintain higher levels of soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium and

*Corresponding author: badiatuabdullahi@gmail.com

overall soil quality than conventional treeless farming systems (Ngaba *et al*., 2024; Kugedera *et al*., 2025).

Among the various agroforestry systems practiced in West Africa, parkland agroforestry is one of the most common traditional farming systems. It is characterized by the deliberate retention of scattered indigenous trees within cultivated fields, where they provide multiple ecological and socioeconomic benefits, including improved soil fertility, erosion control, microclimate regulation and the provision of fuelwood, fodder, fruits, and medicinal products (Bayala *et al*., 2020). These ecological functions contribute to sustainable crop production, particularly under the fragile environmental conditions of the Sudan and Sahel savanna zones.

Previous studies in Nigeria have reported improved soil physicochemical properties under agroforestry systems (Abdulrashid *et al*., 2017; Ahmed *et al*., 2022; Inuwa *et al*., 2024). Similarly, recent global studies have confirmed that agroforestry significantly improves soil physicochemical properties, including organic carbon, nutrient availability and overall soil quality across diverse ecological regions (Ngaba *et al*., 2024; Wolde & Desalegn, 2025; Mesele *et al*., 2025).

Although several studies have investigated the influence of agroforestry on soil fertility in Nigeria (Abdulrashid *et al*., 2017; Ahmed *et al*., 2022; Inuwa *et al*., 2024) most were conducted at single locations or focused on individual tree species. Comparative assessments across multiple Local Government Areas within the semi-arid parkland systems of Northern Katsina State are scarce. Furthermore, few studies have integrated several soil fertility indicators into a single Soil Fertility Index (SFI) for evaluating overall soil quality. This study therefore provides regional evidence by comparing parkland agroforestry and adjacent open farmlands across four LGAs using both individual soil properties and an integrated Soil Fertility Index.

MATERIALS AND METHOD

Study Area

The study was conducted in Katsina State, northwestern Nigeria, located between latitudes 11°00′N and 13°20′N and longitudes 6°45′E and 9°10′E. The state covers approximately 23,938 km² and lies within the Sudan and Sahel savanna ecological zones. It experiences a semi-arid climate characterized by a distinct rainy season (May–September) and a prolonged dry season (October–April). Mean annual rainfall ranges from 500 to 800 mm, while temperatures range from 22 to 42°C (NiMet, 2020). The study was conducted in four Local Government Areas (LGAs) within Katsina North Senatorial District, namely Dutsi, Daura, Baure and Kankia (Figure 1). Representative photographs of the two land-use systems investigated are presented in plate 1a and 1b.

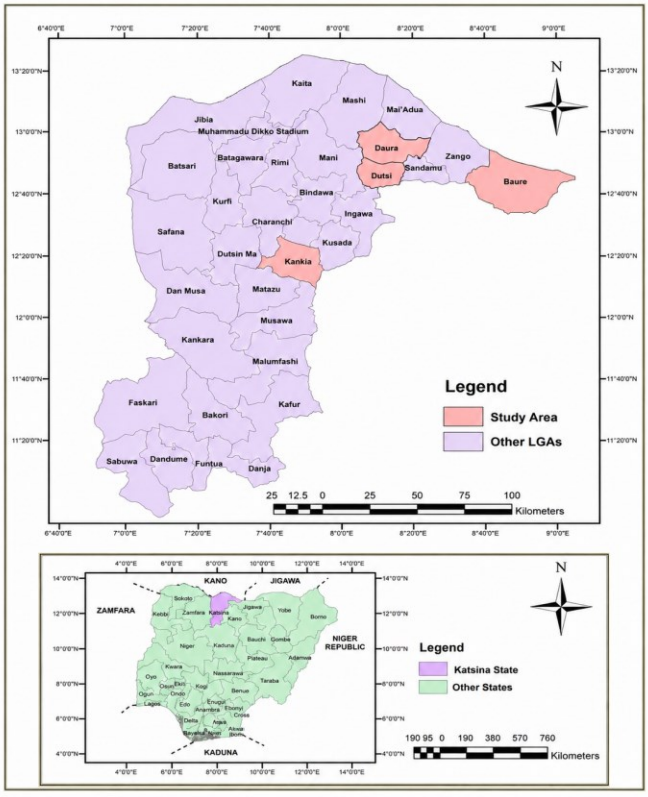


Figure 1: Map of Katsina State, Nigeria, showing the study locations



Plate 1a: Parkland agroforestry



Plate 1b: Open farmland

Sampling Design and Site Selection

A comparative field study was conducted to evaluate selected soil fertility indicators under two land-use systems: parkland agroforestry and adjacent open farmlands. Purposive sampling was used to select eligible farms in the study area. In each Local Government Area, three parkland farms and three adjacent open farmland sites were selected, giving a total of twenty-four sampling sites comprising twelve parkland and twelve open farmland sites. Parkland farms had matured indigenous trees retained within cultivated fields, while adjacent open farmlands had little or no tree cover. The selected farms were comparable in topography, soil conditions, cropping history, and management practices. Purposive sampling was adopted because the study required established parkland agroforestry farms and comparable adjacent open farmlands for direct comparison.

Soil Sample Collection

Soil samples were collected from the topsoil (0–20 cm depth) using a stainless-steel soil auger. At each sampling site, four soil cores were collected randomly and thoroughly mixed to produce one representative composite sample. This resulted in a total of twenty-four composite soil samples (twelve from parkland agroforestry systems and twelve from adjacent open farmlands). The geographic coordinates of each sampling site were recorded using the global positioning system (GPS) function of a smart phone to ensure accurate site identification. Samples were placed in labelled polyethylene bags and transported to the Soil Science Laboratory, Umaru Musa Yar'adua University, Katsina State, Nigeria, for analysis.

Laboratory Analysis

Composite soil samples were air-dried, gently crushed and passed through a 2-mm sieve before analysis for soil pH, organic carbon (OC), organic matter (OM), total nitrogen (TN), available phosphorus (Av. P), and exchangeable potassium (K) using standard procedures. Soil pH was measured in a 1:2.5 soil–water suspension. Organic carbon was determined by the Walkley and Black method (Walkley & Black, 1934), OM was estimated as OC × 1.724, TN by the Kjeldahl method (Bremner, 1996), available phosphorus by the Bray I method (Bray & Kurtz, 1945) and exchangeable potassium by ammonium acetate extraction followed by flame photometry (Thomas, 1982).

Soil Fertility Index (SFI)

A Soil Fertility Index (SFI) was computed to provide an integrated measure of soil fertility. Measured soil properties were standardized using the Z-score transformation:

$$Z = \frac{(X-\mu)}{\sigma} \quad (1)$$

Where X is the observed value, μ is the overall mean, and σ is the standard deviation.

The SFI for each sampling site was calculated as the average of the standardized values of soil pH, organic matter, total nitrogen, available phosphorus and exchangeable potassium:

$$SFI = \frac{(Z_{pH}+Z_{OM}+Z_{TN}+Z_{Av.P}+Z_K)}{5} \quad (2)$$

Where: Z= standardized value, OM = organic matter, TN= total nitrogen, Av.P= available phosphorus and K= exchangeable potassium. Higher SFI values indicate better overall soil fertility.

Statistical Analysis

Data were analyzed using descriptive statistics (mean ± standard deviation) and one-way analysis of variance

(ANOVA) to evaluate differences among location × land-use groups. Where significant differences were detected, Tukey–Kramer post hoc tests were performed for mean separation. Statistical significance was determined at $p < 0.05$.

RESULTS

Soil fertility indicators under parkland and open farmland systems

Parkland agroforestry generally recorded higher mean values of soil pH, organic carbon, organic matter, total nitrogen, available phosphorus and exchangeable potassium than adjacent open farmlands across the study locations (Table 1). Kankia parkland recorded the highest mean values for organic carbon (2.16 ± 0.03%), organic matter (3.72 ± 0.05%), exchangeable potassium (4.09 ± 0.07 cmol kg^{-1}), total nitrogen (0.87 ± 0.06%) and available phosphorus (16.18 ± 1.39 mg kg^{-1}) while Kankia open farmland recorded the lowest mean pH (5.57 ± 0.06). The lowest mean organic carbon (1.18 ± 0.06%) and organic matter (1.88 ± 0.48%) were recorded in Dutsi and Baure open farmlands, respectively, whereas Daura open farmland recorded the lowest mean values of exchangeable potassium (1.70 ± 0.31 cmol kg^{-1}), total nitrogen (0.24 ± 0.06%) and available phosphorus (6.20 ± 0.29 mg kg^{-1}).

Table 1: Mean (± SD) values of selected soil fertility indicators under parkland and open farmland systems across the study locations

Location	Land-Use System	pH	OC(%)	OM (%)	K (cmol kg^1)	TN (%)	Av. P (mg kg^1)
Dutsi	Parkland	6.73 ± 0.05^{a}	1.34 ± 0.07^{b}	2.32 ± 0.12^{b}	3.50 ± 0.10^{b}	0.36 ± 0.04^{c}	12.79 ± 1.49^{b}
Dutsi	Open Farmland	6.13 ± 0.31^{b}	1.18 ± 0.06^{b}	2.04 ± 0.12^{b}	2.88 ± 0.23^{c}	0.28 ± 0.02^{c}	9.17 ± 0.24^{c}
Daura	Parkland	6.87 ± 0.06a	1.33 ± 0.19^{b}	2.29 ± 0.31^{b}	2.78 ± 0.17^{c}	0.27 ± 0.03^{c}	9.47 ± 0.30^{c}
Daura	Open Farmland	6.03 ± 0.37^{b}	1.24 ± 0.04^{b}	2.15 ± 0.15^{b}	1.70 ± 0.31^{d}	0.24 ± 0.06^{c}	6.20 ± 0.29^{d}
Baure	Parkland	6.77 ± 0.06^{a}	1.50 ± 0.08^{b}	2.59 ± 0.14^{b}	3.68 ± 0.13^{b}	0.55 ± 0.12^{b}	11.84 ± 0.84^{b}
Baure	Open Farmland	6.27 ± 0.15^{ab}	1.28 ± 0.06^{b}	1.88 ± 0.48^{b}	3.10 ± 0.14^{bc}	0.33 ± 0.02^{c}	6.90 ± 0.55^{d}
Kankia	Parkland	6.83 ± 0.06^{a}	2.16 ± 0.03^{a}	3.72 ± 0.05^{a}	4.09 ± 0.07^{a}	0.87 ± 0.06^{a}	16.18 ± 1.39^{a}
Kankia	Open Farmland	5.57 ± 0.06^{c}	1.87 ± 0.18^{a}	3.39 ± 0.06^{a}	3.41 ± 0.15^{b}	0.56 ± 0.05^{b}	7.69 ± 0.62^{d}

Values are presented as mean ± SD; n=3 composite soil samples per location × land-use system. Means within the same column sharing the same superscript letter are not significantly different at $p < 0.05$ according to Tukey-Kramer post hoc test. OC = Organic carbon, OM = Organic matter, TN = Total nitrogen, Av. P = Available phosphorus, K = Exchangeable potassium.

One-way analysis of variance (ANOVA) of selected soil fertility indicators across land-use systems and study locations

One-way ANOVA revealed significant differences among the location × land-use groups for all measured soil properties ($p < 0.001$). Soil pH ($F = 20.171$), organic carbon ($F = 32.758$), organic matter ($F = 28.722$), total nitrogen ($F = 39.550$), available phosphorus ($F = 42.863$) and exchangeable potassium ($F = 46.469$) all varied significantly among the groups.

Table 2: One-way ANOVA of selected soil fertility indicators across the eight location–land-use systems

Parameter	Sum of Squares (Between)	Sum of Squares (Within)	f-value	df	p-value
pH	4.707	0.5333	20.171	7,16	<0.0001
OC	2.500	0.1745	32.758	7,16	<0.0001
OM	9.205	0.7325	28.722	7,16	<0.0001
TN	0.9851	0.05693	39.550	7,16	<0.0001
K	239.12	12.751	46.469	7,16	<0.0001
Av.P	10.967	0.5395	42.863	7,16	<0.0001

ANOVA = Analysis of variance, df= Degrees of freedom, OC = Organic carbon, OM = Organic matter, TN = Total nitrogen, Av. P = Available phosphorus, K = Exchangeable potassium.

Soil Fertility Index (SFI) across locations and land-use systems

The Soil Fertility Index (SFI) varied among locations and land-use systems (Table 3). Parkland agroforestry systems consistently recorded higher SFI values than adjacent open farmlands in all four study locations. The highest SFI was recorded in Kankia parkland (1.63 ± 0.06), whereas the lowest value occurred in Daura open farmland (−1.11 ± 0.33). Overall, parkland agroforestry systems recorded a higher mean Soil Fertility Index (0.57 ± 0.74) than adjacent open farmlands (−0.57 ± 0.43). The boxplot (figure 2) illustrates higher distribution and variability of SFI values under parklands compared with open farmlands.

Table 2: Mean (± SD) Soil Fertility Index (SFI) across Parkland and Open Farmland Systems

Location	Land-Use System	Mean SFI ± SD
Dutsi	Parkland	0.27 ± 0.15
Dutsi	Open farmland	-0.55 ± 0.17
Daura	Parkland	-0.18 ± 0.13
Daura	Open farmland	-1.11 ± 0.33
Baure	Parkland	0.54 ± 0.12
Baure	Open farmland	-0.57 ± 0.16
Kankia	Parkland	1.63 ± 0.06
Kankia	Open farmland	-0.04 ± 0.04
Overall	Parkland	0.57 ± 0.74
Overall	Open farmland	-0.57 ± 0.43

Values are presented as mean ± SD; n=3 composite soil samples per location × land-use system. Overall values are presented as mean ± SD; parkland (n = 12) and open farmland (n = 12).

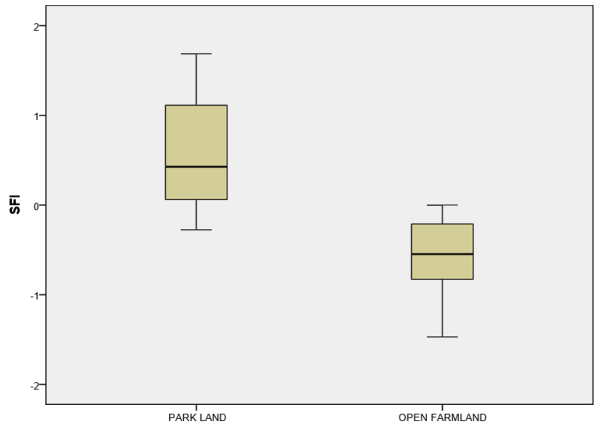


Figure 2: Distribution of Soil Fertility Index (SFI) in the study area

DISCUSSION

This study demonstrated that parkland agroforestry systems significantly improved soil fertility compared with adjacent open farmlands across the four study locations in Northern Katsina State. The consistently higher values of soil pH, organic carbon (OC), organic matter (OM), total nitrogen (TN), available phosphorus (Av. P), exchangeable potassium (K) and Soil Fertility Index (SFI) indicated that integrating indigenous trees into croplands enhances nutrient cycling and improves soil quality under semi-arid conditions. These findings support previous studies reporting that agroforestry promotes sustainable soil management through improved nutrient availability, carbon storage and ecosystem functioning (Ngaba *et al*., 2024; Kugedera *et al*., 2025). More importantly, the present findings demonstrated that these ecological benefits are consistently expressed across different locations in Northern Katsina State, highlighting the resilience of parkland agroforestry under varying environmental conditions.

The higher soil pH observed under parkland agroforestry systems suggests that retained trees improve soil chemical conditions by moderating soil acidification. Continuous decomposition of litter and fine roots releases base-forming cations such as calcium, magnesium and potassium, which neutralize soil acidity and improve nutrient availability. Tree canopies also reduce direct solar radiation, lower soil temperature and minimize moisture loss through evaporation, thereby creating favourable conditions for microbial activity and nutrient mineralization. These interacting processes explain the significantly higher soil pH recorded beneath parkland systems and agree with previous findings reported in Katsina State (Abdulrashid *et al*., 2017; Ahmed *et al*., 2022) and other agroforestry ecosystems (Ngaba *et al*., 2024).

The significantly greater concentrations of organic carbon and organic matter beneath parkland systems reflect continuous additions of leaf litter, twigs, fine roots and other plant residues. These organic materials improve soil aggregation, increase water-holding capacity, stimulate microbial activity and enhance the soil's capacity to retain nutrients. In semi-arid environments where organic matter is rapidly depleted under continuous cultivation, the accumulation of organic residues beneath trees plays a critical role in maintaining long-term soil fertility. Similar improvements in soil organic carbon and organic matter have been reported by Onyegbule *et al*. (2023), Inuwa *et al*. (2024) and Kugedera *et al*. (2025).

Higher total nitrogen under parkland agroforestry systems further demonstrates the important contribution of trees to soil nutrient dynamics. Nitrogen enrichment may result from decomposition of nitrogen-rich litter, increased microbial mineralization, efficient nutrient recycling and biological nitrogen fixation by leguminous tree species where present. Deep-rooted trees also reduce nutrient losses by capturing nutrients that would otherwise be leached below the rooting zone of crops. Consequently, agroforestry systems maintain a more stable nitrogen supply that supports crop productivity and improves soil fertility over time. Similar observations have been reported by Ahmed *et al*. (2022), Ngaba *et al*. (2024) and Wolde and Desalegn (2025).

Available phosphorus and exchangeable potassium were also significantly higher beneath parkland agroforestry systems than in adjacent open farmlands. This improvement can be explained by the nutrient uplift mechanism; whereby deep-rooted trees absorb nutrients from deeper soil layers and subsequently return them to the surface through litterfall and root turnover. Enhanced microbial activity associated with increased organic matter also accelerates nutrient mineralization and improves phosphorus availability. These processes reduce nutrient depletion commonly associated with continuous cultivation in treeless fields and contribute to long-term soil productivity. Similar mechanisms have been reported by Bayala *et al*. (2020), Ahmed *et al*. (2022), and Ngaba *et al*. (2024).

The Soil Fertility Index (SFI) provided an integrated assessment of overall soil quality by combining several key fertility indicators into a single measure. The consistently higher SFI values under parkland agroforestry demonstrate the cumulative positive effects of tree–crop interactions on soil functioning. In contrast, the lower SFI values recorded in adjacent open farmlands may reflect nutrient depletion associated with continuous cultivation, limited organic matter inputs and greater exposure to soil degradation processes. The particularly high SFI recorded in Kankia parkland and the comparatively low value recorded in Daura open farmland indicate spatial variation in soil fertility across the study area. Such variation may be associated with differences in local soil characteristics, land use history, farm management practices and environmental conditions among the sampled locations. Although tree density and parkland tree-species composition were not quantitatively assessed in the present soil study, differences in vegetation structure and management may also contribute to variation in litter inputs, root activity, soil moisture and nutrient cycling. Thus, although parkland

agroforestry consistently improved soil fertility relative to open farmland, the magnitude of improvement varied among locations.

The box plot (Figure 2) shows a clear separation in SFI distributions between the two land-use systems. Parkland agroforestry exhibited generally higher SFI values with the median positioned above that of open farmlands, indicating better overall soil fertility under tree-based systems. The wider spread of SFI values under parkland agroforestry reflects variation among the sampled locations and sites, particularly the high values recorded in Kankia whereas open farmlands generally showed lower and narrower SFI distributions.

CONCLUSION AND RECOMMENDATIONS

This study provides strong empirical evidence that parkland agroforestry is associated with improved soil fertility in Northern Katsina State, as indicated by higher soil pH, organic carbon, organic matter, total nitrogen, available phosphorus, exchangeable potassium and the overall Soil Fertility Index compared with open farmlands. The findings demonstrated that the integration of indigenous trees into croplands is associated with improved soil fertility conditions and may contribute to enhanced nutrient cycling and ecosystem functioning under semi-arid conditions.

Beyond the measured soil fertility outcomes, parkland agroforestry has potential as a nature-based approach for supporting the restoration of degraded lands, strengthening climate resilience and promoting sustainable agricultural production in northern Nigeria. However, these potential benefits were not directly measured in this study and should therefore be considered as implications rather than direct outcomes of the experiment. Conservation and deliberate integration of indigenous multipurpose tree species into farmlands should therefore be strengthened through supportive government policies, farmer awareness programmes and agricultural extension services.

Acknowledgments

The authors are grateful to the Department of Biological Sciences Umaru Musa Yaradua University Katsina for providing academic and laboratory support. We also sincerely appreciate the farmers and local communities in the study areas for their cooperation during field data collection.

Authors' Contributions

BSA conceived the study, connected the data, conducted the field and laboratory work, interpreted the result and drafted the manuscript. SSK supervised the study, contributed to the study design and methodology, reviewed and edited the manuscript. NHW contributed to data interpretation and critically reviewed the manuscript. ULU contributed to manuscript review, editing and intellectual input. All others read and approved the final manuscript.

Ethical Statement

Ethical approval for this study was obtained from the Ministry of Environment, Katsina State. Permission was obtained from relevant community leaders before field work commenced. Farmers were given informed consent before accessing their farmlands.

AI Declaration Statement

The authors used AI, mainly ChatGPT and Grammarly solely to improve clarity, grammar and structure of the manuscript.

REFERENCES

Abdulrashid, L., Yaro, A., & Ibrahim El-Ladan, Y. (2017). Assessment of soil conditions under two agroforestry systems in Rimi and Batagarawa Local Government Areas of Katsina State, Nigeria. *Direct Research Journal of Agriculture and Food Science, 5*(10), 338–347. https://doi.org/10.26765/DRJAFS.2017.9423

Ahmed, M., Danjuma, M. N., & Zakariya, M. M. (2022). Effects of *Faidherbia albida* Del. A. Chev. on soil properties in agroforestry parkland ecosystem in Garki Village, Katsina State, Nigeria. *Renewable, 1*(1), 44–52. https://journals.ui.edu.ng/index.php/ren/article/view/679

Ayeni, M. J., Oyun, M. B., Adeyemo, A. J., Fasinmirin, J. T., Jayeoba, O. J., & Lawal, S. O. (2025). Evaluation of selected soil physicochemical properties for integrated soil fertility management in agricultural communities in Southern and Northern Nigeria. *Discover Applied Sciences, 7*, 1–16. https://doi.org/10.1007/s42452-025-07389-0

Bayala, J., Sanou, J., Bazié, H. R., Coe, R., Kalinganire, A., & Sinclair, F. L. (2020). Regenerated trees in farmers' fields increase soil carbon across the Sahel. *Agroforestry Systems, 94*(2), 401–415. https://doi.org/10.1007/s10457-019-00403-6

Brady, N. C., & Weil, R. R. (2016). *The nature and properties of soils* (15th ed.). Pearson.

Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science, 59*(1), 39–46. https://doi.org/10.1097/00010694-194501000-00006

Food and Agriculture Organization of the United Nations. (2021). *The state of the world's land and water resources for food and agriculture: Systems at breaking point*. FAO. https://doi.org/10.4060/cb7654en

Inuwa, A., Adeduntan, S. A., Adekunle, V. A. J., & Wali, B. R. (2024). Assessment of soil physicochemical properties in the parklands of Northern Nigeria. *African Journal of Environment and Natural Science Research, 7*(1), 146–154. https://doi.org/10.52589/AJENSR-NJGUL6F1

Kugedera, A. T., Trivedi, A., Nandeha, N., & Biswas, A. (2025). Agroforestry and integrated nutrient management as climate-smart agro-technologies for soil health and climate change mitigation: A review on African and Asian regions. *Discover Agriculture, 3*, 272. https://doi.org/10.1007/s44279-025-00463-6

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal, 112*(5), 3265–3277. https://doi.org/10.1002/agj2.20282

Mesele, S. A., Adelana, F. O., & Mechri, M. (2025). Soil fertility improvement in agroforestry after 30 years of silvopasture on ferric lixisols within the Guinea Savanna ecology of Nigeria. *Trees, Forests and People, 20*, 100847. https://doi.org/10.1016/j.tfp.2025.100847

Mogale, T. E., Mashava, T., Mamabolo, E., Mugari, E., Mabitsela, K. E., & Ayisi, K. K. (2026). Agroforestry and degraded croplands restoration in Sub-Saharan Africa: A systematic review. *Agroforestry Systems, 100*, 193. https://doi.org/10.1007/s10457-026-01581-w

Mpongwana, S., Manyevere, A., & Mupangwa, J. (2024). Improving soil fertility through dual inoculation with arbuscular mycorrhizal fungi and Rhizobium on a eutric cambisol cultivated with forage legumes in a semi-arid region. *Heliyon, 10*(2), e24817. https://doi.org/10.1016/j.heliyon.2024.e24817

Ngaba, M. J. Y., Mgelwa, A. S., Gurmesa, G. A., Uwiragiye, Y., Zhu, F., Qiu, Q., Fang, Y., Hu, B., & Rennenberg, H. (2024). Meta-analysis unveils differential effects of agroforestry on soil properties in different zonobiomes. *Plant and Soil, 496*, 589–607. https://doi.org/10.1007/s11104-024-06590-5

Nigerian Meteorological Agency. (2020). *Climate data report of Katsina State*. NiMet.

Onokebhagbe, V. O., Adam, I. A., Mohamed, S., & Joseph, J. (2025). Soil organic carbon stocks in semi-arid saline soils of Dutse, Northern Nigeria. *FUDMA Journal of Agriculture and Agricultural Technology, 11*(1), 38–46. https://doi.org/10.33003/jaat.2025.1101.05

Onyegbule, U. N., Onwudike, S. U., Opara-Nadi, N., & Opara-Nadi, O. (2023). Soil fertility evaluation and land-use effects on soil properties, carbon and nitrogen sequestration in the rainforest of Nigeria. *Eurasian Journal of Soil Science, 12*(4), 310–319. https://dergipark.org.tr/en/pub/ejss/issue/77854/1327155

Sekhar, M., Lallawmkimi, M. C., Rani, D. V., Upadhyay, L., Tiwari, P., Verma, U., & Rajput, A. (2024). Agroforestry practices and their impact on soil health and fertility: A review. *Journal of Experimental Agriculture International, 46*(9), 511–528. https://doi.org/10.9734/jeai/2024/v46i92849

Thomas, G. W. (1982). Exchangeable cations. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis: Part 2. Chemical and microbiological properties* (2nd ed., Agronomy Monograph No. 9, pp. 159–165). American Society of Agronomy.

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science, 37*(1), 29–38. https://doi.org/10.1097/00010694-193401000-00003

Wolde, A., & Desalegn, S. (2025). Impact of nitrogen-fixing trees in agroforestry on soil physicochemical properties and crop productivity in Ethiopia: A systematic review. *Archives of Agronomy and Soil Science*. https://doi.org/10.1080/03650340.2025.2545190