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Physicochemical Characterization of Agricultural Soils under Chlorpyrifos Contamination

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Abstract

The intensification of agricultural activities in the Lower Niger River Basin, Ilorin, Nigeria, has led to repeated applications of chlorpyrifos, raising concerns regarding its effect on soil physicochemical properties. This study investigated the influence of chlorpyrifos contamination on pH, temperature, moisture content, water holding capacity, organic matter, and soil texture in agricultural soils. Guided by environmental chemistry principles governing pesticide–soil interactions, the research employed a quantitative, cross-sectional design. Soil samples were systematically and purposively collected from three farms, with composite samples taken at 0–15 cm depth. Physicochemical analyses were conducted using precision-calibrated instruments, validated through triplicate measurements, and data analysed via descriptive statistics and one-way ANOVA with post hoc Tukey’s HSD tests at $\alpha = 0.05$, with effect size (η^2) also calculated to quantify the proportion of variance attributable to site differences. Results revealed significant differences ($p < 0.001$) and extremely large effect sizes for soil pH and water holding capacity across sites, while temperature, moisture content, and organic matter showed no significant differences ($p > 0.05$) despite medium to large effect sizes. Soils were predominantly sandy, with low moisture retention and organic content, suggesting limited fertility and vulnerability to environmental stress. The findings suggest potential associations between pesticide exposure and changes in selected soil physicochemical parameters. It is recommended that integrated soil remediation and monitoring strategies be adopted to mitigate pesticide-induced soil degradation in the region.

Keywords: Chlorpyrifos, Soil, Physicochemical Properties, Pesticide, Contamination.

Introduction

The intensification of agricultural production in developing economies has resulted in a sustained increase in pesticide inputs into soil systems, thereby raising concerns about their long-term chemical behaviour and environmental persistence. Chlorpyrifos, an organophosphate insecticide widely applied in crop protection, remains detectable in agricultural soils due to its moderate hydrophobicity, adsorption affinity, and resistance to rapid hydrolysis under certain environmental conditions (Racke, 2020; Silva *et al.*, 2019).

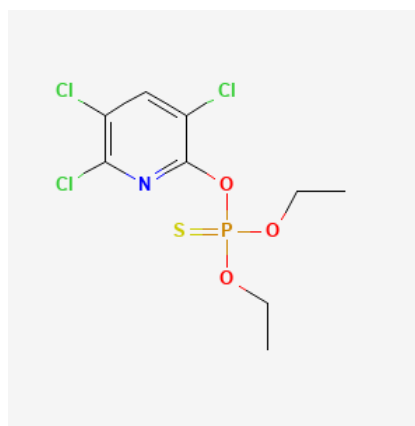
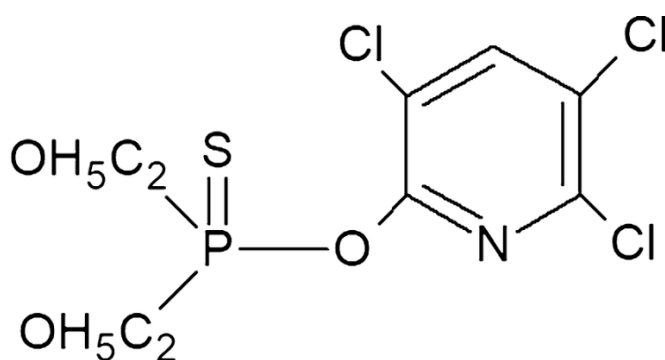


Fig1. Chemical structure of Chlorpyrifos

Source: Shalini *et al.*(2020)

Within the framework of environmental chemistry, the compound's fate in soil is governed primarily by physicochemical interactions such as sorption–desorption equilibria, hydrolytic stability, pH-dependent degradation pathways, and interactions with soil organic fractions rather than biological processes alone. These interactions directly influence soil parameters including acidity, moisture retention, structural texture, and nutrient availability, which collectively determine soil functionality and productivity (Gebremariam *et al.*, 2012; FAO, 2021). In regions such as Nigeria where pesticide regulation, monitoring, and residue tracking remain inconsistent, repeated chlorpyrifos applications may gradually alter soil chemical balance, thereby posing risks to agricultural sustainability and environmental safety. Consequently, understanding the influence of chlorpyrifos contamination on soil physicochemical properties is essential for evaluating agro-ecosystem resilience and guiding evidence-based soil management strategies.

Recent scholarship reviews across global, African, and Nigerian contexts have increasingly emphasised the environmental chemistry of pesticide residues, particularly their capacity to modify soil properties beyond immediate toxicological effects. Studies conducted in Asia and Europe have demonstrated that organophosphate residues may alter soil pH buffering capacity, reduce cation exchange efficiency, and influence organic carbon stability (Silva *et al.*, 2019; Udoekpo *et al.*, 2021). Within Africa, investigations in Ghana, Kenya, and South Africa similarly report detectable pesticide accumulation in agricultural soils and associated changes in soil chemical indices, although most analyses remain limited to residue quantification rather than broader physicochemical implications (Fianko *et al.*, 2020; Olisah *et al.*, 2020). Nigerian studies have confirmed widespread pesticide presence in farming systems and highlighted weak enforcement of safety regulations, yet they largely emphasise exposure risk and residue detection in crops rather than systematic evaluation of soil chemical transformations (SRADeV Nigeria, 2020; Udoekpo *et al.*, 2022). These trends reveal several research gaps, including a conceptual gap in linking pesticide contamination with soil physicochemical functionality, a methodological gap in integrating multi-parameter soil chemistry assessments, and a contextual gap in basin-level investigations within Nigerian irrigation zones. Addressing these limitations provides both theoretical value for environmental chemistry and practical relevance for sustainable land use management.

Despite existing research on pesticide contamination, the exact environmental problem confronting many Nigerian agricultural soils is not merely the presence of chlorpyrifos residues but the uncertainty regarding how such residues influence soil physicochemical integrity over time. Soil systems function as dynamic chemical matrices where alterations in pH, organic matter stability, moisture retention, and thermal conditions serve as sensitive indicators of chemical disturbance because these parameters regulate sorption–desorption processes, microbial activity, and nutrient transformation pathways within the soil environment. Consequently, even subtle pesticide-induced shifts in these physicochemical properties may cumulatively reduce fertility, alter nutrient cycling efficiency, and compromise long-term productivity (Food and Agriculture Organization, 2021). The Lower Niger River Basin represents a particularly important case because of its extensive irrigated farming activities and repeated agrochemical use, yet systematic environmental chemistry assessments of pesticide–soil interactions within this region remain scarce. Existing studies often adopt either toxicological or microbiological perspectives, leaving a

clear analytical gap regarding the chemical processes governing soil transformation under pesticide exposure. This study therefore seeks to resolve this empirical and contextual gap by examining the extent to which chlorpyrifos contamination influences measurable soil physicochemical parameters. In doing so, it positions soil properties as dependent variables reflecting environmental change, while pesticide contamination serves as the principal independent chemical driver.

Guided by these considerations, the present research is anchored on the premise that soil physicochemical characteristics provide measurable indicators of pesticide-induced environmental alteration. The study therefore investigates whether chlorpyrifos contamination significantly modifies soil parameters including pH, temperature, moisture content, organic matter, texture, and water-holding capacity within agricultural soils of the Lower Niger River Basin. Establishing this relationship is necessary not only for validating environmental chemistry models of pesticide–soil interaction but also for informing regulatory frameworks and sustainable soil management practices in Nigeria and comparable agro-ecological zones. The research questions and hypotheses emerging from this premise are designed to test whether statistically significant differences exist in soil physicochemical properties across contaminated sites, thereby linking empirical observation with theoretical expectations of pesticide behaviour in soil matrices. Through this approach, the study contributes to contemporary environmental chemistry discourse by providing region-specific evidence on pesticide-driven soil transformation while strengthening the analytical bridge between contamination processes and soil quality assessment.

Research Question

The specific objective of the study is to:

- Assess the physicochemical properties of agricultural soil contaminated by chlorpyrifos.

Null Hypothesis (H_0):

The following hypotheses were formulated for this study.

- There is no significant difference in selected physicochemical properties of soils exposed to repeated chlorpyrifos application

Alternative Hypothesis (H_1):

- There is significant difference in selected physicochemical properties of soils exposed to repeated chlorpyrifos application.

Materials & Method

This study employed a quantitative research design grounded in standard environmental chemistry protocols for soil physicochemical characterisation. A cross-sectional sampling approach was adopted, enabling comparative assessment of multiple field sites contemporaneously to the period of soil collection. The design focused on objective quantification of pH, temperature, water retention, moisture content, and organic matter parameters known to influence soil chemical dynamics and pollutant fate (Soil pH: Techniques, Challenges and Insights, 2024). Soil sample selection was systematic and purposive, targeting three distinct farms with history of frequent chlorpyrifos usage within the Lower Niger River Basin Authority, Ilorin, Kwara State, Nigeria. Soil samples were collected from (Location A: 8.51178°N, 4.599215°E; B: 8.510855°N, 4.599485°E; C: 8.510712°N, 4.599842°E). At each farm, sampling was conducted at 0–15 cm depth, reflecting the standard practice for surface soil assessment where pesticide accumulation and chemical interactions predominantly occur. Composite samples were obtained by combining subsamples taken from the four corners and centre of each farm plot to reduce spatial heterogeneity and measurement bias. All samples were placed in chemically inert polyethylene bags, labelled with unique identifiers, and maintained at ambient temperature before laboratory analysis. Samples were transported to the analytical laboratory in the Department of Microbiology, University of Ilorin, Kwara state, Nigeria for physicochemical properties analysis. The number of sampling sites and replicates was determined based on standard soil physicochemical assessment protocols used in exploratory environmental chemistry studies where triplicate laboratory measurements are considered adequate to ensure analytical precision and reduce measurement error. Composite sampling from multiple subsites within each farm further improved representativeness of soil conditions while maintaining manageable laboratory workload.

The analysis of the physicochemical properties of the soil samples was conducted using a comprehensive set of laboratory glassware and equipment calibrated for precision and reproducibility. Soil suspensions were prepared in borosilicate glass beakers of 250 mL capacity, while conical flasks of 250 mL were used for pH measurements and controlled mixing of soil-water solutions. Accurate volumetric measurements were obtained using graduated cylinders of 100 mL, and volumetric flasks of 250 mL were employed to prepare standard buffer solutions for pH meter calibration. Soil samples for moisture content and organic matter determination were weighed in porcelain crucibles (25 mL) with fitted lids and dried in a laboratory oven maintained

at 105 °C to constant weight, after which the samples were cooled in a desiccator containing silica gel to prevent reabsorption of atmospheric moisture. Stirring of soil suspensions was achieved using 20 cm borosilicate glass rods, and glass funnels (100 mm) were used for decanting supernatants, while graduated pipettes (25 mL) and micropipettes enabled precise addition of reagents. Soil homogenisation prior to analysis was performed using a porcelain mortar and pestle, and large debris was removed using a sieve set of 2 mm and 1 mm mesh sizes to ensure uniform particle size. Temperature measurements were recorded in situ using a digital soil thermometer with ± 0.1 °C accuracy, while soil pH was determined using a digital pH meter equipped with a glass electrode calibrated at pH 4.00, 7.00, and 10.00. Soil water holding capacity was evaluated using pre-weighed metal tins and 250 mL beakers to standardise saturation, and controlled heating during organic matter analysis was performed using a Bunsen burner and adjustable hotplate. All weights were recorded using an analytical balance with 0.0001 g sensitivity, and sampling locations were georeferenced using a GPS device accurate to ± 3 m, ensuring spatial precision. Data recording and replication were maintained systematically using laboratory notebooks and an electronic data logger, providing traceability and adherence to quality control protocols consistent with contemporary environmental chemistry research (Soil Moisture Measuring Techniques, 2022; World Soil Information Service, 2023; Evaluation of selected soil physicochemical properties, 2025).

Soil Texture

Soil texture was preliminarily assessed using the hand-texturing (feel) method as described by Gee and Or (2002). Approximately one tablespoon of air-dried soil free from visible debris was placed in the palm and gradually moistened with distilled water until a plastic consistency was achieved. The moistened soil was kneaded between the thumb and forefinger to evaluate tactile characteristics including grittiness, smoothness, and plasticity. The ability of the soil to form a ribbon when pressed between the thumb and forefinger was also examined as an indicator of clay content. Based on these tactile properties, the soil was classified into general textural categories using the USDA Soil Texture Triangle.

- Sand: Feels gritty and rough. Individual particles are easily felt and do not stick together well.
- Silt: Feels smooth and silky. When moist, it feels like flour or talcum powder.
- Clay: Feels sticky, plastic, and moldable. Can be easily shaped into ribbons or thin sheets.

This method provides a rapid field-based estimation of soil texture. However, it is qualitative in nature and does not provide precise particle-size distribution. In this study, the feel method was used to provide a preliminary classification of soil texture suitable for comparative assessment of the sampled soils.

Soil Temperature

The temperature measures the degree of hotness or coldness of a material. To measure soil temperature, a soil thermometer was inserted into a fresh pilot hole (2-3 inches deep). Reading was taken after 20-30 minutes and recorded. The procedure was done in triplicate and the mean value was recorded (Grand & Lavkulich, 2012). Soil temperature measurements were performed in situ using a Hanna HI98509 digital soil thermometer with a stainless-steel probe of 12 cm length and ± 0.1 °C resolution, inserted to a consistent depth of 10–15 cm to capture representative thermal conditions affecting chemical equilibria, solute mobility, and adsorption kinetics.

Soil pH

pH is a measure of hydrogen ion concentration, a quantitative measure of the acidity or alkalinity of a solution. The pH of the soil samples was determined by using Aneja, (2014) method through weighing 20g of soil sample in a 250mL beaker and 20mL of distilled water was added to arrive at 1:1 ratio. The suspension was left for 20 minutes with occasional stirring with a glass rod. The pH meter was then calibrated using standard buffer solutions. The pH probe was inserted into the suspension and pH reading was taken and recorded. The procedure was done in triplicate and the mean value was recorded. Soil pH was quantified potentiometrically using a Mettler Toledo FiveEasy™ FE20 benchtop pH meter fitted with a double-junction glass combination electrode (model InLab® Expert Pro), capable of ± 0.01 pH resolution and ± 0.1 °C temperature compensation. Prior to each analytical session, the instrument was rigorously calibrated with certified standard buffer solutions at pH 4.00, 7.00, and 10.00, prepared from high-purity reagents (Merck, $\geq 99.5\%$) and verified for stability at 25 °C, ensuring precise measurement of hydrogen ion activity across acidic, neutral, and alkaline ranges (Najdenko *et al.*, 2024).

Moisture Content

Soil moisture content refers to the amount of water present in the soil, typically expressed as a percentage of the soil's dry weight or as a volumetric percentage. To determine the moisture content of soil sample, Dubey and Maheshwari, (2005) method was used. Two crucibles were dried in an oven at a temperature of 105⁰ C for 24 hours. The crucibles were then cooled in a desiccator

and their weight measured separately. One gram of soil sample was weighed into each crucible and dried in an oven at a temperature of 105⁰ C for 24 hours. Each crucible with sample contained was weighed and weight of each dried sample was calculated. The procedure was done in triplicate and the mean value was recorded.

$$\% \text{ moisture} = \frac{\text{Loss in weight of sample (g)}}{\text{Initial weight of sample (g)}} \times 100 \quad \dots\dots\dots \text{Equation 1}$$

Organic Matter

Soil organic matter is the fraction of the soil that consists of plant or animal tissue in various stages of breakdown (decomposition). Soil organic matter content was determined using the loss-on-ignition (LOI) method in a programmable muffle furnace (Carbolite CWF 1300) set to 550 °C for 4 h, ensuring complete combustion of labile organic carbon while minimising thermal decomposition of mineral constituents. Prior to combustion, 5 g aliquots of air-dried, sieved soil were weighed to ±0.0001 g on the analytical balance, placed in pre-weighed crucibles, and evenly distributed to ensure uniform heat exposure. Post-combustion mass loss was calculated as a percentage of initial dry soil mass, providing a robust estimate of total soil organic carbon content, a key determinant of cation exchange capacity, nutrient retention, and overall soil fertility (Najdenko *et al.*, 2024; Spring *et al.*, 2024). Throughout all procedures, pipettes, volumetric flasks, and borosilicate beakers used for solution preparation were calibrated to ±0.1 mL, ensuring accuracy in all reagent additions, while replicate analyses (n = 3 per sample) were performed to quantify analytical precision and support statistical reliability of the dataset.

The procedure was done in triplicate and the mean value was recorded.

$$\% \text{ organic matter} = \frac{\text{Loss in weight of sample (g)}}{\text{Initial weight of sample (g)}} \times 100 \quad \dots\dots\dots \text{Equation 2}$$

Water Holding Capacity

Soil water holding capacity (WHC) refers to the amount of water a soil can hold against the force of gravity, and it's influenced by factors like soil texture, organic matter content, and particle size. To determine the WHC of soil sample, Aneja, (2014) method was used. Water holding capacity (WHC) was determined by gravimetric saturation techniques in accordance with standard soil physics procedures, using pre-weighed stainless-steel tins (diameter 7 cm, height 10 cm, 150 g empty weight) filled to 75% with oven-dried soil. Soil saturation was achieved by immersing tins

in a distilled water bath until capillary equilibration, after which the mass of water absorbed was quantified with an analytical balance (Sartorius Entris®, 0.0001 g readability), yielding WHC values expressed as grams of water per gram of oven-dry soil. Gravimetric moisture content was assessed by oven-drying approximately 5 g of homogenised soil in porcelain crucibles (25 mL, fitted lids) at 105 ± 2 °C for 24 h until constant mass was achieved, followed by cooling in a desiccator containing silica gel to prevent atmospheric rehydration; moisture content was then calculated as the percentage mass loss relative to the initial wet weight (Najdenko *et al.*, 2024; Oyun *et al.*, 2025).

$$\text{WHC} = \frac{\text{weight of water absorbed (Z-Y) (g)}}{\text{weight of oven dried soil (Y-X) (g)}} \dots\dots\dots \text{Equation 3}$$

Prior to analysis, all instruments were calibrated using certified reference solutions or standards to ensure accuracy and traceability of measurements. The pH meter was calibrated at pH 4.00, 7.00, and 10.00 using standard buffer solutions, with calibration checks performed every batch of ten samples. Equipment precision for temperature and gravimetric measurements was verified using replicates and quality check standards, ensuring that analytical variability remained within ± 2 % of true value thresholds commonly accepted in soil chemistry research. All laboratory procedures adhered to quality control protocols outlined in international soil testing manuals and recent methodological reviews (World Soil Information Service, 2023). Validation of methods was reinforced through the use of triplicate analyses for every parameter measured, with mean values and standard deviations reported to reflect within-sample variation.

Data collection protocols were systematic, structured, and executed by trained analysts to reduce procedural bias and maintain consistency across all soil parameters. Each soil parameter was measured independently, and results were logged electronically in a dedicated laboratory information management system to prevent transcription errors. Metadata including sampling date, instrument calibration logs, and sample handling conditions were recorded contemporaneously to support transparency and reproducibility. Where applicable, chemical reagents used were of analytical grade, and glassware was pre-cleaned and rinsed with deionised water prior to use. Collected data comprised continuous variables for pH, temperature, moisture content, WHC, organic matter percentage, and categorical classification for texture, facilitating rigorous statistical analyses.

The resulting dataset underwent statistical analysis using IBM SPSS Statistics v26.0. Descriptive statistics were computed for all physicochemical parameters to characterise mean and standard deviations (SD). Inferential analysis included one-way analysis of variance (ANOVA) to test for significant differences among soil sites with respect to measured properties, with significance thresholds set at $\alpha=0.05$. Where significant F values were observed, post-hoc pairwise comparisons using Tukey's HSD were executed to delineate site-specific differences in parameters such as pH and WHC. In addition to significance testing, effect sizes (η^2) were calculated to quantify the proportion of variance explained by site differences. Normality and homogeneity of variance assumptions were verified prior to hypothesis testing, ensuring the robustness of statistical inferences.

Results and Discussions

Physicochemical Properties of the Soil Samples

The analysis of the different physical and chemical soil parameters revealed the range of temperature, pH, water holding capacity, moisture content, organic matter content, and the type of soil texture.

Temperature (°C) of the Soil Samples

The mean value of the temperature of the three soil samples were within the range of 30°-30.67°C. Sample A and B happen to have same temperature value of 30.67°C while sample C had a lower temperature value of 30°C as shown in Table 1.

Analysis of Variance (ANOVA) for Temperature of the three soil samples

ANOVA test shows a high P value (0.214) than 0.05 level of significance, there by indicating no significant differences between the temperatures of the three soil samples as shown in Table 2.

Table 1

Temperature Range of Soil Samples

Field	Temperature (oC)			Mean±SD
	1	2	3	
A	31	30	31	30.67±0.58
B	31	31	30	30.67±0.58
C	30	30	30	30.00±0.00

Table 2***Analysis of Variance (ANOVA) for Temperature of the Soil Samples***

Source of Variation	Sum of Squares (SS)	Degree of Freedom (DF)	Mean Square (MS)	F-Statistics	P-Value	F Critical	Decision
Between Groups	0.89	2	0.44	2.00	0.214	5.143	Not Significant
Within Groups	1.33	6	0.22	—	—	—	
Total	2.22	8	-	—	—	—	

The pH Condition of the Soil Samples

The mean pH of the three soil samples was within the range of 7.22-8.39. Sample C had the highest Ph value while sample A had the lowest value. This result indicate that pH of sample A is neutral while pH of sample B and sample C were moderately alkaline as shown in Table 3.

Analysis of Variance (ANOVA) for pH of the Soil Samples

Table 4 Shows the ANOVA test result having a very low P value (<0.001) and a wide margin between F statistics (229.47) and F Critical (5.143) indicating a highly significant difference between the pH value of the three soil samples.

Post hoc Test for pH of the Soil Samples

Table 5 shows the Tukey's Honestly Significant Difference (HSD) test for Multiple Comparisons of pH value of soil samples. Tukey's HSD shows that there is significant difference between sample A vs B, A vs C, and B vs C when comparing the temperature value.

Table 3***The pH range of soil sample***

Sample	pH			Mean±SD
	1	2	3	
A	7.13	7.33	7.21	7.22±0.10
B	7.99	8.12	8.09	8.07±0.07
C	8.43	8.39	8.36	8.39±0.04

Table 4***Analysis of Variance (ANOVA) for pH of the three soil samples***

Source of Variation	Sum of Squares (SS)	Degree of Freedom (DF)	Mean Square (MS)	F-Statistics	P- Value	F Critical	Decision
Between Groups	2.74	2	1.37	229.47	<0.001	5.143	Highly Significant
Within Groups	0.036	6	0.006	—	—	—	
Total	2.78	8	-	—	—	—	

For one-way ANOVA, effect size is reported using Eta squared (η^2).

Formula

$$\eta^2 = \frac{SS_{between}}{SS_{total}}$$

From Table 4:

- SS_between = **2.74**
- SS_total = **2.78**

$$\eta^2 = \frac{2.74}{2.78} = 0.986$$

0.986 is an extremely large effect. One-way ANOVA revealed a highly significant difference in soil pH among the three sampling sites, $F_{(2,6)} = 229.47$, $p < 0.001$, $\eta^2 = 0.986$, indicating that site location explained approximately 98.6% of the total variance in soil pH.

Table 5***Tukey's Honestly Significant Difference (HSD) Test for Multiple Comparisons of pH Value of Soil Samples***

Comparison	Mean 1	Mean 2	Difference	HSD Critical	Decision	P Value
Sample A vs Sample B	7.22	8.07	0.85	0.195	Significant	<0.001

Sample A vs Sample C	7.22	8.39	1.17	0.195	Significant	<0.001
Sample B vs Sample C	8.07	8.39	0.35	0.195	Significant	<0.001

Water Holding Capacity of the Soil Samples

The mean water holding capacity of the three soil samples were within the range of 0.17-0.32%. Sample B had the highest water holding capacity while sample A had the least water holding capacity value as seen in Table 6. However, these values showed a very low water holding capacity of sample A, B, and C.

Analysis of Variance (ANOVA) for Water Holding Capacity of the Samples.

ANOVA test shows a very low P value (<0.001) and wide margin between F statistics (35.86) and F Critical (5.143) indicating a highly significant difference between the water holding capacity value of the three soil samples as shown in Table 7.

Post Hoc Test for Water Holding Capacity of the Soil Samples

Tukey's HSD shows that there is significant difference between sample A vs B, B vs C but A vs C are not Significantly different when comparing the water holding capacity value as shown in Table 6.

Table 6
The Water Holding Capacity Range of Soil Samples

Sample	Water Holding Capacity (%)			Mean±SD
	1	2	3	
A	18	16	19	17±0.01
B	31	36	29	32±0.03
C	22	18	21	22±0.02

Table 7
Analysis of Variance (ANOVA) for Water Holding Capacity of the Soil Samples

Source of Variation	Sum of Squares (SS)	Degree of Freedom (DF)	Mean Square (MS)	F-Statistics	P- Value	F Critical	Decision
Between Groups	0.041	2	0.0205	35.86	<0.001	5.143	Highly Significant
Within Groups	0.0034	6	0.0005	—	—	—	
Total	0.044	8	-	—	—	—	

Table 8
Tukey's HSD for Water Holding Comparisons of the Soil Samples

Comparison	Mean 1	Mean 2	Difference	HSD Critical	Decision	P value
Sample A vs Sample B	0.177	0.320	0.143	0.060	Significant	<0.001
Sample A vs Sample C	0.177	0.203	0.026	0.060	Not Significant	0.42
Sample B vs Sample C	0.320	0.203	0.117	0.060	Significant	<0.001

From Table 7:

- $SS_{\text{between}} = 0.041$
- $SS_{\text{total}} = 0.044$

$$\eta^2 = \frac{0.041}{0.044} = 0.9318 \approx 0.932$$

Extremely large effect. One-way ANOVA revealed a highly significant difference in water holding capacity among the three soil samples, $F_{(2,6)} = 35.86$, $p < 0.001$, $\eta^2 = 0.932$, indicating that sample type accounted for approximately 93.2% of the total variance in water holding capacity.

The Moisture Content Range of Soil Samples

The mean moisture content of the three soil samples was within the range of 1.70-2.67%. Sample B had the highest moisture content while sample A had the least moisture content value. However, these values showed very low moisture content of sample A, B, and C as seen in Table 9.

Analysis of Variance (ANOVA) for moisture content of the three samples

ANOVA test shows a high P value (0.131) and a F statistics value (2.93) lower than F critical (5.143) indicating no significant difference among the moisture content of the three soil samples as shown in Table 10

Table 9
The Moisture Content Range of Soil Samples

Sample	Moisture Content (%)			Mean±SD
	1	2	3	
A	1.89	1.47	1.73	1.70±0.21
B	3.43	2.17	2.39	2.67±0.67
C	1.60	1.93	2.97	2.17±0.71

Table 10
Analysis of Variance (ANOVA) for Moisture Content of the Soil Samples

Source of Variation	Sum of Squares (SS)	Degree of Freedom (DF)	Mean Square (MS)	F-Statistics	P- Value	F Critical	Decision
Between Groups	1.85	2	0.925	2.93	0.131	5.143	Not Significant
Within Groups	1.89	6	0.315	—	—	—	
Total	3.74	8	-	—	—	—	

From Table 10:

- $SS_{\text{between}} = 1.85$
- $SS_{\text{total}} = 3.74$

$$\eta^2 = \frac{1.85}{3.74} = 0.4947 \approx 0.495$$

Large effect size, even though the difference was not statistically significant. One-way ANOVA indicated no significant difference in moisture content among the three soil samples, $F_{(2,6)} = 2.93$, $p = 0.131$, $\eta^2 = 0.495$, suggesting that approximately 49.5% of the total variance could be attributed to sample type, although this did not reach statistical significance.

The Organic matter content range of soil sample A, B, and C.

The mean organic matter content of the three soil samples was within the range of 0.22-0.28%. Sample B had the highest organic matter content while sample A had the least moisture content value. However, these values showed a very low organic matter content of sample A, B, and C as shown in Table 11.

Analysis of Variance (ANOVA) for organic matter content of the three soil samples

ANOVA test shows a high P value (0.786) and a F statistics value (0.25) lower than F critical (5.143) indicating no significant difference among the organic matter content of the three soil samples as seen in Table 12.

Table 11

The Organic Matter Content Range of Soil Samples

Sample	Organic Matter Content (%)			Mean±SD
	1	2	3	
A	0.17	0.28	0.21	0.22±0.05
B	0.38	0.35	0.12	0.28±0.14
C	0.10	0.38	0.29	0.26±0.15

Table 12

Analysis of Variance (ANOVA) for Organic Matter Content of the Soil Samples

Source of Variation	Sum of Squares (SS)	Degree of Freedom (DF)	Mean Square (MS)	F-Statistics	P- Value	F Critical	Decision
Between Groups	0.0067	2	0.00335	0.25	0.786	5.143	Not Significant
Within Groups	0.080	6	0.0133	—	—	—	
Total	0.087	8	-	—	—	—	

From Table 12:

- $SS_{\text{between}} = 0.0067$
- $SS_{\text{total}} = 0.087$

$$\eta^2 = \frac{0.0067}{0.087} = 0.077 \approx 0.077$$

Medium effect, but not significant. One-way ANOVA indicated no significant difference in organic matter content among the three soil samples, $F_{(2,6)} = 0.25$, $p = 0.786$, $\eta^2 = 0.077$, suggesting that sample type accounted for approximately 7.7% of the total variance, which is a medium effect size but not statistically significant.

Soil Texture Property of Soil Samples

Analysis of soil texture indicates that all the three soil samples have a uniform sand texture property since they are gritty, rough, and their particles doesn't stick together when wet as seen in Table 13.

Table 13
Soil Texture of Soil Samples

Sample	Soil Texture	Property
A	Sand	Gritty, rough., and particles doesn't stick together
B	Sand	Gritty, rough., and particles doesn't stick together
C	Sand	Gritty, rough., and particles doesn't stick together

Discussions

The physicochemical analysis of the soil samples revealed important characteristics of the sampled agricultural soils, including soil texture, pH, temperature, organic matter content, moisture content, and water holding capacity.

The mean pH values of samples A, B, and C were 7.22, 8.07, and 8.39, respectively. According to the Soil Survey Manual (2017), sample A falls within the neutral range, while samples B and C are moderately alkaline. One-way ANOVA revealed a highly significant difference among the three sites ($p < 0.001$) with a very large effect size, $\eta^2 = 0.986$, indicating that site location accounted for approximately 98.6% of the total variance in soil pH. This suggests that the observed variation in pH is strongly influenced by site-specific environmental or management factors rather than random variability. Soil pH is primarily controlled by mineral composition, irrigation water quality, fertiliser application, and accumulation of carbonate or bicarbonate ions in the soil matrix (Hartmann & Six, 2023). In irrigated agricultural systems, particularly in semi-arid or tropical environments, the gradual accumulation of soluble salts and basic cations such as calcium and magnesium may shift soil pH toward moderately alkaline conditions. Similar pH ranges have been reported in tropical agricultural soils influenced by irrigation and fertiliser inputs (FAO, 2021). The pH value observed in sample A (7.22) lies within the commonly recommended range of 6.0–7.5, which is optimal for nutrient availability and plant growth, whereas the moderately alkaline conditions observed in samples B and C may alter nutrient solubility and chemical equilibria within the soil system (Horiba, 2024).

Soil temperature values were relatively uniform across sites, with 30.67 °C for samples A and B and 30.0 °C for sample C. One-way ANOVA indicated no significant difference among the sites, $F_{(2,6)} = 2.00$, $p = 0.214$, $\eta^2 = 0.400$, suggesting that local temperature variation contributed minimally to differences in other soil parameters. Statistical analysis indicated no significant difference among the sites ($p = 0.214$), implying that temperature conditions were relatively uniform across the sampled farms. This outcome is expected given the close geographical proximity of the sampling locations and their exposure to similar climatic conditions. Soil temperature is primarily controlled by solar radiation, soil moisture, vegetation cover, and seasonal climatic conditions. The observed temperature range corresponds with the typical range reported for tropical agricultural soils, generally between 20 °C and 30 °C, which supports active soil chemical reactions and plant growth (Dove *et al.*, 2021). Comparable temperature conditions have also been reported in tropical soils supporting typical mesophilic soil processes (Chiara and Mario, 2015). The absence of statistically significant temperature variation therefore suggests that temperature did not contribute substantially to differences in other soil parameters across the sites.

The water holding capacity (WHC) of the soil samples ranged from 17% in Sample A to 32% in Sample B, with Sample C showing an intermediate value of 22%. Sample B exhibited the highest WHC ($32 \pm 3 \%$), while Sample A had the lowest ($17 \pm 1 \%$), and Sample C had $22 \pm 2 \%$. ANOVA revealed a highly significant difference among the samples, $F(2,6) = 35.86$, $p < 0.001$, with an extremely large effect size ($\eta^2 = 0.932$), indicating that approximately 93.2% of the variance in WHC is attributable to inherent soil properties rather than sampling variability. Post hoc analysis using Tukey's HSD indicated significant differences between Sample A vs B (0.143) and B vs C (0.117), while A vs C (0.026) was not significant. The higher WHC observed in Sample B likely reflects slightly greater organic matter content and modest differences in soil pore structure, which enhance moisture retention. Mechanistically, WHC is strongly influenced by soil texture, pore size distribution, and organic matter content. Soils dominated by coarse particles such as sand typically contain large macropores that allow rapid drainage, limiting water retention, whereas clay-rich soils with abundant micropores retain water more effectively. Similar low WHC values have been reported in sandy agricultural soils across tropical environments, where limited clay content and low organic matter reduce the soil's capacity to store water (Wang *et al.*, 2021; Mario, 2015).

Soil moisture content is an important indicator of water availability within the soil profile. The moisture content of the three soil samples ranged from 1.70% (Sample A) to 2.67% (Sample B), with Sample C at 2.17%. One-way ANOVA showed no statistically significant difference among the sites, $F_{(2,6)} = 2.93$, $p = 0.131$, although the effect size was large ($\eta^2 = 0.495$), suggesting that approximately 49.5% of the variance could be attributed to sample type despite the lack of statistical significance. This suggests that the small variations in measured moisture content likely reflect short-term environmental fluctuations rather than inherent soil property differences. In tropical climates, soil moisture dynamics are strongly influenced by rainfall patterns, evapotranspiration rates, and seasonal climatic variability. During periods of limited rainfall or elevated temperature, evaporation from the soil surface and transpiration from vegetation can significantly reduce soil moisture levels (Ibno Namr & Bel-Lahbib 2023). The relatively low moisture values observed across the sites therefore likely reflect the combined influence of sandy soil texture and prevailing climatic conditions at the time of sampling.

The organic matter content of the soil samples ranged from 0.22% in Sample A to 0.28% in Sample B, with Sample C at 0.26%, indicating generally low levels of organic material in the soils. One-

way ANOVA confirmed no significant differences among the sites ($F_{(2,6)} = 0.25$, $p = 0.786$), with a small-to-medium effect size ($\eta^2 = 0.077$), suggesting that only 7.7% of the total variance could be attributed to site differences. Soil organic matter plays a critical role in improving soil structure, enhancing nutrient retention, and increasing water holding capacity. However, coarse-textured soils often contain relatively low organic matter concentrations because their large particles provide limited surface area for the stabilisation of organic materials. Previous soil studies have similarly reported that sandy soils typically contain less than 1% organic matter, whereas loamy or clay-rich soils often exhibit higher concentrations due to greater particle surface area and improved organic matter stabilisation (Hartmann & Six, 2023). The low organic matter levels observed in the present study therefore correspond with the sandy nature of the soils identified through texture analysis.

The hand-texturing assessment indicated that all three soil samples were predominantly sandy in texture. The soils exhibited a gritty and rough feel when moistened and rubbed between the fingers, and the particles did not adhere together easily. These characteristics are typical of soils dominated by sand particles. It should be noted that the hand-texturing (feel) method provides a qualitative estimate of soil texture and is commonly used for rapid field classification. More precise determination of soil particle size distribution is usually performed using laboratory techniques such as hydrometer or pipette analysis recommended by the Food and Agriculture Organization and the United States Department of Agriculture. Consequently, the texture results obtained in this study are interpreted as preliminary classifications rather than definitive quantitative measurements. Despite this limitation, the sandy nature of the soils identified through the tactile assessment is consistent with the physicochemical properties observed in the study. Sandy soils are generally characterized by high permeability, rapid drainage, and relatively low capacity to retain water and nutrients. These properties correspond with the low moisture content, reduced water holding capacity, and lower organic matter levels recorded in the analyzed samples. Similar relationships between sandy soil texture, low organic matter content, and reduced moisture retention have been reported in tropical agricultural soils (Cycoń *et al.*, 2016). Therefore, although the texture determination was qualitative, the observed soil properties collectively support the classification of the study soils as sand-dominated.

In summary, the combined analysis of ANOVA effect sizes and physicochemical measurements indicates that soil pH and WHC exhibit extremely large site-dependent differences, while moisture content shows a large but non-significant effect, and organic matter demonstrates medium effect with minimal site variance. These findings underscore the role of inherent soil characteristics, particularly texture and mineral composition, in regulating water and nutrient availability, and provide a basis for site-specific soil management strategies in sandy agricultural soils.

Conclusions

The study demonstrates that while soil pH and temperature across the sampled sites remain within optimal ranges for plant growth and microbial activity, the markedly low water holding capacity, organic matter content, and moisture levels indicate constrained soil fertility and weak water retention. These deficiencies, exacerbated by the sandy texture of the soils, suggest increased vulnerability to environmental stress and reduced agricultural productivity, particularly during the dry season. Findings underscore the need for soil management strategies, including organic amendments and moisture conservation practices, to improve soil quality and sustain crop growth. However, the study is limited by absence of pesticide residue quantification here.

Recommendations

Based on this research, the following recommendations were made;

1. Regular monitoring of pesticide residues and soil physicochemical properties, coupled with targeted soil remediation, is essential to maintain fertility and prevent degradation.
2. Adoption of judicious pesticide application and integrated pest management strategies can safeguard soil health and enhance agro-ecosystem resilience.

Declarations

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used Claude (Anthropic) for grammatical structuring, language editing, and improving the clarity and readability of the manuscript. The author(s) carefully reviewed and edited all AI-generated suggestions as needed and take full responsibility for the accuracy, integrity, and content of the published article.

Ethical approval

This study did not involve human participants, animals, human data, or biological materials requiring ethical approval. The research consisted solely of the collection and physicochemical analysis of agricultural soil samples. All sampling and laboratory procedures were conducted in accordance with relevant institutional guidelines, environmental regulations, and accepted standards of good scientific practice.

Clinical Trial Number

Not applicable.

Consent to Participate

Not applicable. This research involved laboratory analysis of soil samples without human or animal subjects.

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Consent to Publish

All authors (OLAOSUN, Sanjo; ADEGBOYE, Emmanuel Timilehin; and AGBABIKA, Toyin Olayemi) consent to the publication of this manuscript in an academic journal.

Author Contributions

O.S.: Conceptualization, investigation, field sampling, data collection, methodology, and validation.

A.E.T.: Data curation, formal analysis, statistical analysis, visualization, manuscript writing (original draft), review and editing.

A.T.O.: Supervision, project administration, methodological guidance, critical review, editorial input, and final approval of the manuscript.

All authors contributed to the conception and design of the study, discussed the results, reviewed the manuscript critically for important intellectual content, approved the final version of the manuscript, and agree to be accountable for all aspects of the work.

Data availability

The datasets for the results as analysed during the current study are available via Google Drive at:

https://docs.google.com/document/d/1TlxwprF2mreep2oaaTAanijCaytpzY5Z/edit?usp=drive_link&ouid=100585276033877568999&rtpof=true&sd=true

Competing Interests

The authors declare that they have no known competing financial or non-financial interests, personal relationships, or affiliations that could have appeared to influence the work reported in this manuscript.

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