

Comparative Analysis of Physicochemical Properties and Heavy Metal Concentrations in Fadama and Non-Fadama Soils of Bwari Area Council, Abuja, Nigeria

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ABSTRACT

This study evaluates Fadama (lowland) and Non-Fadama (upland) soils across Kubwa, Bwari, and Ushafa in FCT Abuja, Nigeria employing 2×3 Factorial Design resulting in six treatment combinations. Eighteen composite samples were taken from the Fadama and Non-Fadama farms surface horizon (0–30 cm) during the dry season using a multistage stratified random sampling technique.. The samples were prepared and analyzed in triplicate for their physicochemical properties using Standardized analytical techniques of AOAC (Association of Official Analytical Chemists) and SSSA (Soil Science Society of America) methods. Data obtained were subjected to analysis of variance. The soils are predominantly coarse-textured and sand-dominated (70.91%–90.00%). Two-Way ANOVA indicated significant differences among the physicochemical properties ($P < 0.05$). Pearson correlation indicated correlation among the parameters temperature exhibits a near-perfect positive correlation with Nickel ($r = 0.955$). Baseline properties show stable pH (5.7–6.9) and Cation Exchange Capacity (17.81–21.55 cmol(+)/kg), but reveal major constraints: severe lowland compaction (up to 1.81 g/cm³), organic carbon depletion, and critical phosphorus deficiency (0.14–1.46 mg/kg). Among the toxic heavy metals, lithogenic Nickel is naturally elevated (>108 mg/kg) which might be due the presence of specific magmatic or metamorphic rock types like peridotite, dunite, serpentinite, or pyroxenite which naturally contain high concentrations of nickel (often 1,000 to 3,000+ mg/kg).

Received: 14 Sep. 2026

Accepted: 17 Sep. 2026

Published: 30 Sep. 2026

Keywords: Cation Exchange Capacity, Fadama Soils, Heavy Metals, Physicochemical Properties, Soil Compaction, Soil Texture, Spatial Variability

INTRODUCTION

Soil represents the fundamental natural bedrock of global agricultural productivity, environmental stability, and essential ecosystem services, including water purification, carbon sequestration, and biodiversity support (Batjes *et al*, 2019). Its physicochemical characteristics such as pH, electrical conductivity (EC), organic matter content, cation exchange capacity (CEC), particle size distribution, and macro/micronutrient concentrations (N, P, K, Ca, Mg, Zn, Fe) directly govern soil fertility, biochemical nutrient cycling, and resilience against abiotic stresses (Batjes *et al*, 2019; FAO & ISRIC, 2024). Global soil assessments, including the World Soil Information Service (WoSIS) database, indicate that over 33% of global soils suffer from advanced degradation driven by water erosion, secondary salinization, acidification, and continuous nutrient depletion, posing severe risks to global food security (Batjes *et al*, 2019; FAO & ISRIC, 2024). In West Africa, farmland is split into two main types: *fadama* (seasonally flooded lowlands) and non-*fadama* (rain-fed uplands). Fadama areas produce 2 to 5 times more crops because their fine soil traps nutrients and holds water from seasonal floods. Fadama has high level of moisture in any season of the year and are classified as hydromorphic soils (Okeahialam *et al*, 2006). They are also known for high cation exchange capacity, organic matter, and available phosphorous (P), Total Nitrogen (N) and micro nutrients than upland soils (Singh, 2003). Due to their long time retention of moisture all year round, Fadama soils are considered suitable for cultivation of crops, and because they receive water from both natural and human sources, which impact on cleansing polluted water, recharging underground

aquifers, they resist the risk of flood and drought (Okeahialam *et al*, 2006). The soils have been reported to be fragile ecosystem and their conversion to cropland may result in severe ecological and environmental degradation if not properly done (Babalola *et al.*, 2011).

In contrast, non-*fadama* uplands have sandy soils, lower pH levels (5.0 - 6.5), and dry out quickly (World Bank, 2024). In Nigeria, *fadama* projects have increased farm income by up to 154%. However, most small farmers still rely on non-*fadama* uplands, which suffer from topsoil erosion, organic matter loss, and poor nutrient retention (World Bank, 2024; Barnabas *et al*, 2025). The Federal Capital Territory (FCT) shows this clear difference. The upland soils formed from weathered rock are mostly sandy loams (70 - 85% sand) that hold very little water and have low organic carbon (under 1.2%). On the other hand, stream valleys in areas like Bwari, Kubwa, and Ushafa have fertile *fadama* pockets with richer soil and more moisture (Iniubong *et al*, 2023). However, while uplands suffer from soil erosion, nearby *fadama* lowlands are being lost to urban building at a rate of 5–10% every year (Barnabas *et al*, 2025). Past studies show that while *fadama* lowlands store more calcium (Ca²⁺) and magnesium (Mg²⁺), they risk becoming too salty (EC > 2.0 dS/m) under continuous irrigation. Meanwhile, non-*fadama* uplands lose essential minerals like Zinc (Zn) and Iron (Fe) because water easily washes them through the sandy ground (Oyetola & Fasina, 2024). Therefore proper uses of soils for agricultural purposes require detailed knowledge of the properties of the soils to discover their limiting characteristics and recommend appropriate measures. Soil physico-chemical

properties evaluation can influence our decisions on how to improve its fertility, quality and productivity.

This study aimed to compare physicochemical and heavy metals status of fadama and non-fadama soils in Kubwa, Bwari, and Ushafa communities within Bwari Area Council, Federal Capital Territory, Abuja, Nigeria with the view to providing relevant information for its sustainable agricultural production exploitation. Understanding these differences helps create practical farming strategies, such as building soil ridges to prevent upland erosion and managing salt buildup in the lowlands for farmers across the Bwari Area Council.

MATERIALS AND METHODS

Location and Geography

Bwari Area Council in the Federal Capital Territory (FCT), Nigeria, lies between latitudes 8°55'N to 9°30'N and longitudes 7°20'E to 7°45'E. It covers approximately 1,024 km² within the Guinea savanna agroecological zone (National Population Commission, 2022). The council borders Kaduna State to the north, Nasarawa State to the east, Abuja Municipal Area Council to the south, and Gwagwalada Area Council to the west. This location near the capital city exposes the area to intense land-use pressures caused by rapid urban expansion.

Sampling and Sample Collection

Soils of six (6) study farm locations were randomly sampled at three (3) observational points in each location. The three observational points in each location served as the replicates. The sampled areas were determined by the slope, soil type, and cropping history of the areas. This was carried out in all the six farm locations. The soil samples were collected at the depths of 0-30, at three (3) replicates each for the six locations. Therefore, total of eighteen (18) soil samples were collected for the study. Soil samples collected were bagged, properly labeled and taken to a laboratory for the determination of physical and chemical properties. The field sampling was scheduled for a continuous two-week dry-season period (February 28 to March 14, 2026) to guarantee safe access to flooded lowlands, minimizes soil moisture distortions, and avoids rain interference on each selected farm.

Sample Preparation

All 18 composite samples were first logged into laboratory registers with tracking codes (LAB-001 through LAB-036). Next, the composite samples were spread on clean plastic trays at 25–30°C for 5–7 days to air-dry until reaching a constant weight. Once dry, the soils were crushed gently with a wooden pestle and passed through a 2 mm stainless steel sieve, with gravel (>2 mm) weighed and recorded as a percentage of total mass while the fine earth (<2 mm) was stored in labeled containers. Finally, a 100 g subsample of the fine earth is ground further through a 0.5 mm sieve for Organic Carbon (OC) and Total Nitrogen (TN) testing.

Physical Analysis

Particle Size Distribution (Hydrometer Method)

The Particle Size distribution of the soil samples was determined following Bouyoucons hydrometer method as outlined in Gee and Or (2002).

Silt was calculated by difference:

$$\text{Silt \%} = 100 - (\text{Sand \%} + \text{Clay \%})$$

Soil textural classes were determined using the USDA texture triangle.

Bulk Density (Core Method)

Core samples were dried at 105°C for 24 hours to obtain the dry soil mass (M-dry). Bulk density (pb) was calculated relative to total core volume ($V_{\text{core}} = \pi r^2 h$):

$$\text{pb (g/cm}^3\text{)} = (\text{M dry}/V_{\text{core}})$$

Chemical Analysis

Soil pH and Electrical Conductivity (EC)

Measured in 1:2.5 soil-to-water (H₂O) and 0.01 M CaCl₂ extracts using calibrated digital meters. EC was measured on the settled 1:2.5 water supernatant using a conductivity meter calibrated against 0.01 M KCl.

Organic Carbon (Walkley-Black Titration Method)

1.00 g of fine soil (<0.5 mm) was digested with 10 mL of 1 N K₂Cr₂O₇ and 20 mL of concentrated H₂SO₄. After sitting for 30 minutes, the solution was diluted with water and back-titrated against standard ferrous ammonium sulfate using ferroin indicator.

Total Nitrogen (Modified Kjeldahl Method)

1.00g of soil was digested with concentrated H₂SO₄ and a selenium catalyst tablet at 370°C. Digestates are distilled into boric acid and titrated with standard 0.01 M HCl.

Available Phosphorus (Bray No. 1 Method)

2.5g of soil was extracted using 0.03 M NH₄F + 0.025 M HCl solution. Phosphorus concentration was determined colorimetrically using ascorbic acid blue development on a spectrophotometer (882 nm).

Exchangeable Cations and CEC (Ammonium Acetate Extraction)

Soil was extracted with 1.0 NH₄OAc (pH 7.0). Calcium (Ca²⁺) and magnesium (Mg²⁺) were measured via Atomic Absorption Spectrometry (AAS), while potassium (K⁺) and sodium (Na⁺) were measured using flame photometry. Total Cation Exchange Capacity (CEC) was determined by displacing absorbed NH₄⁺ with 1 M KCl followed by distillation titration.

Heavy Metal Digestion and Instrument Analysis (EPA Method 3050B)

Soil samples undergo open-vessel acid digestion: 1.00 g of fine soil (<2 mm) was digested with 10mL of concentrated HNO₃ (65%) at 95°C. The process was repeated until brown NO₂ fumes stop. 3 mL of 30% H₂O₂ was added in steps to destroy organic matter. 5 mL of concentrated HCl and 10 mL of deionized water were added, followed by refluxing for 15 minutes. Cooled digestates were filtered through Whatman No. 42 filter paper into 50 mL volumetric flasks. Heavy metal (Cd, Cr, Mn, Zn, Ar, Pb, Mg and Cu) concentrations were measured using Flame AAS (FAAS) at specific wavelengths (Cd 228.8 nm, Cr 357.9 nm, Mn 279.5 nm, Zn 213.9 nm. Mercury (Hg) was quantified using Cold Vapor AAS (CVAAS) at 253.7 nm using stannous chloride (SnCl₂) as a reducing agent.

Data Analysis Plan

All the laboratory data were analyzed using standard statistical software (SPSS v28 / R). The analytical workflow includes:

Descriptive Statistics

Means, standard deviations, and coefficients of variation (CV %) calculated per parameter across land types and communities.

Two-Way Analysis of Variance (ANOVA)

Applied to evaluate the main effects of Land Type, Location, and their Interaction (Land Type $\times$ Location) at $\alpha = 0.05$.

Correlation Analysis

Pearson's correlation matrix constructed to assess relationships Sbetween soil parameters (e.g., Organic Matter vs. CEC, pH vs. Micronutrient availability).

RESULTS AND DISCUSSION**Table1: Particle Size Analysis of Fadama and Non-Fadama Soil**

Location & Soil Type	Sand (%)	Clay (%)	Silt (%)	Textural Class
Fadama Soils				
Bwari Fadama 1	60.39	23.72	15.89	Sandy loam
Bwari Fadama 2	50.00	18.00	32.00	Sandy loam
Bwari Fadama 3	58.85	31.15	10.00	Sandy loam
Kubwa Fadama 1	58.14	21.86	10.00	Sandy loam
Kubwa Fadama 2	70.00	15.00	15.00	Sandy loam
Kubwa Fadama 3	49.31	27.24	13.45	Sandy loam
Ushafa Fadama 1	56.21	26.90	16.89	Loamy
Ushafa Fadama 2	51.67	30.00	18.33	Loamy
Ushafa Fadama 3	56.19	22.70	21.11	Loamy
Non-Fadama Soils				
Bwari Non-Fadama 1	60.00	20.00	20.00	Loam
Bwari Non-Fadama 2	84.62	11.54	3.84	Sandy
Bwari Non-Fadama 3	70.91	5.49	23.60	Sandy loam
Kubwa Non-Fadama 1	81.80	18.20	0.00	Sandy
Kubwa Non-Fadama 2	76.00	20.00	4.00	Sandy
Kubwa Non-Fadama 3	72.22	20.40	7.38	Sandy
Ushafa Non-Fadama 1	90.00	10.00	0.00	Sandy
Ushafa Non-Fadama 2	83.64	12.73	3.63	Sandy
Ushafa Non-Fadama 3	82.76	10.34	6.90	Sandy

Table2: Physicochemical Analysis of Fadama and Non-Fadama Soil Samples collected From Bwari, Kubwa and Ushafa

Parameter	Bwari Fadama (bf)	Kubwa Fadama (Kf)	Ushafa Fadama (Uf)	Bwari Non-Fadama (bnf)	Kubwa Non-Fadama (Knf)	Ushafa Non-Fadama (Unf)
Soil pH	5.7	6.3	5.8	5.9	6.9	6.8
Soil Structure	Single grain	Granular	Single grain	Single grain	Granular	Single grain
Soil Color	Light brown	Brownish	Deep Grey	Reddish brown	Light brown	Dark yellow
Temp (°C)	26	26	25	25	26	26
Avg. Moisture (%)	18.7	9.6	11.9	5.3	10.1	6.9
Bulk Density (g/cm ³)	1.81	1.25	1.55	1.20	1.45	1.49
Specific Gravity	1.87	2.21	2.17	2.41	2.35	2.18
Conductivity (μS/cm)	76.0	112.0	39.0	20.0	228.0	116.0
Organic Carbon (%)	1.99	0.75	2.02	0.87	0.75	1.79
Organic Matter (%)	3.43	1.29	3.48	1.50	1.29	3.09
Total Nitrogen (%)	0.35	0.21	0.35	0.21	0.42	0.14
Avail. Phosphorus (mg/kg)	0.25	0.14	1.46	0.19	0.99	0.35
CEC (cmol(+)/kg ⁻¹)	20.18	21.55	20.99	21.48	21.53	17.81

Table 3: Heavy Metal Profiles of Target Soils (mg/kg)

Metal Analyzed	Bwari Fadama	Kubwa Fadama	Ushafa Fadama	Bwari Non-Fadama	Kubwa Non-Fadama	Ushafa Non-Fadama
Arsenic (As)	< LOD	< LOD	0.002	< LOD	0.002	0.002
Mercury (Hg)	< LOD	< LOD	0.002	< LOD	0.003	< LOD
Lead (Pb)	< LOD	1.60	< LOD	< LOD	< LOD	4.09
Cadmium (Cd)	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
Copper (Cu)	16.26	26.63	23.17	39.40	33.86	33.33
Zinc (Zn)	14.38	4.32	17.74	3.39	11.45	11.34
Magnesium (Mg)	307.20	70.60	227.90	170.90	235.16	155.13
Nickel (Ni)	79.83	117.99	18.69	23.33	114.84	108.19
Chromium (Cr)	6.29	1.14	2.47	2.35	3.14	5.63

Table 4: Descriptive Statistical Summary of Evaluated Soil Horizons by Location

Location And Soil Regime	N	Mean	Deviation Std.	Std. Error99%	Confidence Interval For Mean
Bwari Fadama	18	364.43	392.20	92.44	[96.51, 632.35]
Kubuwa Fadama	18	363.44	391.32	92.23	[96.13, 630.76]
Ushafa Fadama	18	349.30	382.60	90.18	[87.94, 610.66]
Bwari Non-Fadama	18	369.23	390.69	94.76	[92.47, 646.00]
Kubwa Non-Fadama	18	360.45	389.60	91.83	[94.30, 626.59]
Ushafa Non-Fadama	18	372.86	398.24	93.87	

Table 5: Two-Factor ANOVA (Without Replication) of the Parameters Studied

SUMMARY	Count	Sum	Average	Variance		
6.9	15	574.06	38.27066667	6179.658821		
6.8	15	513.87	34.258	3947.621874		
6.3	15	378.73	25.24866667	3229.615312		
5.8	15	337.69	22.51266667	1883.486592		
5.9	15	576.27	38.418	4388.331417		
5.7	15	489.75	32.65	2540.667157		
Temp (°C)	6	154	25.66666667	0.266666667		
Avg. Moisture (%)	6	62.5	10.41666667	22.02566667		
Bulk Density (g/cm ³)	6	8.75	1.458333333	0.048656667		
Specific Gravity	6	13.19	2.198333333	0.035376667		
Conductivity (µS/cm)	6	591	98.5	5493.5		
Organic Carbon (%)	6	8.17	1.361666667	0.400336667		
Organic Matter (%)	6	18.11	3.018333333	0.226936667		
Total Nitrogen (%)	6	1.68	0.28	0.01176		
Avail. Phosphorus (mg/kg)	6	3.38	0.563333333	0.289666667		
CEC (cmol(+)/kg-1)	6	123.54	20.59	2.13076		
Copper (Cu)	6	172.65	28.775	70.42763		
Zinc (Zn)	6	62.62	10.43666667	31.56010667		
Magnesium (Mg)	6	1166.89	194.4816667	6585.650097		
Nickel (Ni)	6	462.87	77.145	2074.65391		
Chromium (Cr)	6	21.02	3.503333333	4.080706667		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	3323.315	5	664.66305	0.683174882	0.637695	2.345586
Columns	242268.1	14	17304.86502	17.78683067	9.4E-18	1.835683
Error	68103.23	70	972.9032305			
Total	313694.7	89				

Table 6: Result of Pearson Correlation Analysis of the Physicochemical Properties of the Study Areas

Soil pH	Temp (°C)	Avg. Moisture (%)	Bulk Density (g/cm ³)	Specific Gravity	Conductivity (µS/cm)	Organic Carbon (%)	Organic Matter (%)	Total Nitrogen (%)	Avail. Phosphorus	CEC (cmol(+)/kg-1)	Cu	Zn	Mg	Ni	Cr
1															
0.272	1														
96															
0.766	0.299	1													
424	838														
-	0.292	0.1267	1												
0.285	633	67654													
23															
-	-	-	-	1											
0.708	0.377	0.8695	0.3751												
54	51	47119	2239												
0.337	0.721	-	-	0.0030	1										
52	108	0.0977	0.1648	58356											
		15187	4016												
0.185	-	0.5309	0.7027	-	-	1									
108	0.102	94735	66993	0.7340	0.4969										
	019			48769	9169										
0.643	0.046	0.3377	0.1615	-	0.2459	0.5236	1								
428	07	14151	58164	0.6330	76106	07901									
				68863											
0.248	2.48	0.6079	-	-	-	0.0632	-	1							
146	E-17	27959	0.0760	0.1647	0.3117	51872	0.3769								
			85456	31693	8329		92384								

Soil pH	Temp (°C)	Avg. Moisture (%)	Bulk Density (g/cm³)	Specific Gravity	Conductivity (µS/cm)	Organic Carbon (%)	Organic Matter (%)	Total Nitrogen (%)	Avail. Phosphorus	CEC (cmol(+)/kg-l)	Cu	Zn	Mg	Ni	Cr
-	-	0.1271	0.3004	0.1227	-	0.2840	-	0.6380	1	-	-	-	-	-	-
0.182	0.376	36893	29161	57189	0.4708	0.3967	0.1828	52994	-	-	-	-	-	-	-
62	595	-	-	-	8435	-	98232	-	-	-	-	-	-	-	-
0.284	-	0.0390	-	0.3761	0.0244	-	-	0.4935	0.1890	1	-	-	-	-	-
689	0.342	61985	0.8644	755	56709	0.6030	0.2776	04715	464	-	-	-	-	-	-
-	269	-	4463	-	-	37131	34031	-	-	-	-	-	-	-	-
-	-	-	-	0.9096	-	-	-	-	-	0.0392	1	-	-	-	-
0.854	0.231	0.9253	0.1781	97976	0.0128	0.6261	0.6527	0.3928	0.1312	35673	-	-	-	-	-
82	674	234	1045	-	6961	82459	02267	29493	9954	-	-	-	-	-	-
0.128	-	0.6148	0.6775	-	-	0.8022	0.1656	0.5660	0.7125	-	-	1	-	-	-
898	0.017	24321	78487	0.5541	0.4829	91282	71575	04072	95029	0.3023	0.6	-	-	-	-
-	695	-	-	01497	1027	-	-	-	-	67159	06	-	-	-	-
0.117	-	0.6987	0.2721	-	-	0.5393	-	0.7216	0.3738	-	-	0.7	1	-	-
578	0.046	31002	19965	0.4913	0.6629	0107	0.2459	98059	61111	0.0424	0.4	099	-	-	-
-	946	-	-	87534	7935	-	58606	-	-	21572	57	-	-	-	-
0.128	0.954	0.0527	0.2134	-	0.8336	-	-	-	-	-	-	-	-	-	1
591	633	84507	5003	0.1165	52751	0.3128	0.0409	0.0836	0.3344	0.2527	0.0	0.1	0.2	-	-
-	-	-	-	33701	-	40586	83446	12953	6238	95734	17	73	78	-	-
-	0.419	0.4644	0.6888	-	-	0.6597	0.0578	0.0185	-	-	-	0.4	0.6	0.	1
0.012	238	82192	49038	0.6587	0.2493	78705	25464	33382	0.1797	0.7531	0.3	86	11	19	-
12	-	-	-	53808	9174	-	-	-	9209	92142	35	-	-	-	-

Discussion

Particle Size Distribution and Textural Classification

The particle size analysis (Table i) reveals a predominant coarse-textured matrix across both Fadama (wetland) and Non-Fadama (upland) soils in Bwari, Kubwa, and Ushafa. Sand fractions dominate across all sampling horizons ranging from 49.31 % to 70.00% in Fadama soils and 60.00% to 90.00% in Non-Fadama soils due to the parent material weathering of the underlying crystalline basement complex characteristic of the Federal Capital Territory (FCT), Abuja. Within this matrix, Fadama soils exhibit textural classes ranging from Sandy loam to loam where higher silt contents (up to 32.00 % in Bwari Fadama 2) reflect continuous alluvial deposition during seasonal flooding events. Non-Fadama soils range from Sandy to Sandy clay, with sub-surface clay accumulation (up to 23.60% in Bwari Non-Fadama 3) indicating typical pedogenic clay illuviation. Soil bulk density spans between 1.20 g/cm³ and 1.81 g/cm³ across all locations; while most sites fall within the normal range for root growth, Bwari Fadama 1 reaches 1.81 g/cm³ and exceeds the critical threshold of 1.60 g/cm³, presenting a severe risk of soil compaction that could restrict root elongation and oxygen diffusion (Akinwumi & Ojetayo, 2022).

Soil Physicochemical Properties and Heavy Metal Profiles

Evaluation of soil chemical properties (Table 2 and Table 3) indicates favorable agronomic conditions for several key baseline parameters across the studied sites. Soil pH values range from 5.7 to 6.9 as shown in table 2, placing the soils in a moderately acidic to near-neutral range that aligns with the ideal agricultural window of 6.0–8.5 (Iniubong *et al*, 2023). Electrical conductivity remains low across all locations (20.0 to 228.0 µS/cm), sitting well beneath the critical salinity hazard threshold of 4,000 µS/cm and confirming non-saline conditions (World Bank, 2022). Furthermore, Soil Organic Matter (1.29% to 3.43%) and Total Organic Carbon (0.75% to 2.02%) match standard Southern Guinea Savannah baseline values, with Fadama sites exhibiting slightly elevated organic pools due to reduced decomposition rates under seasonal moisture saturation (Chivenge *et al*, 2020; Barnabas *et al*, 2025). According to Solomon *et al* (2026) “Soils in the Nigerian savanna often have low organic matter and are usually moderately to strongly acidic”. Beyond general baseline stability, the soil displays optimal nutrient buffering capacity alongside clear structural fertility potential. Cation Exchange Capacity values (17.81 to 21.55 cmol(+)/kg) also demonstrate robust cation buffering and strong nutrient retention capacity, surpassing the standard

baseline threshold of 10.0–15.0 cmol(+)/kg (Zakari *et al*, 2021). This elevated exchange capacity indicates a strong inherent ability to retain essential plant nutrients and prevent rapid macro-cation leaching. Overall, these findings demonstrate that the target soils possess solid physical and chemical stability, providing a fertile foundation for agricultural productivity when supported by targeted nutrient management. Despite these favorable baseline parameters, a critical nutrient imbalance was observed regarding primary macronutrient availability: Total Nitrogen reserves remain moderate (0.14% to 0.42%), but Available Phosphorus is severely deficient across all horizons (0.14 to 1.46 mg/kg) when compared against the optimal agricultural baseline of 15.0–30.0 mg/kg. This acute phosphorus limitation stems primarily from intense phosphate fixation and structural occlusion onto iron and aluminum oxide complexes—a biogeochemical process characteristic of highly weathered tropical soils—while heavy metal concentrations (Cd, Pb, As, Cr, Cu, Zn) remain safely within WHO/FAO permissible limits, posing zero immediate phytotoxic risk.

Note: < LOD = Not Detected.)

Inferential Statistics and Correlation Dynamics

The empirical statistical properties, including descriptive parameters and Two-Way ANOVA results, demonstrate intra-site baseline uniformity across the target study sites (Tables 4–5). Two-factor ANOVA without replication indicates that variation across sampling sites was not statistically significant ($p = 0.638$), whereas variations among parameters were highly significant ($p < 0.001$).

The Pearson correlation matrix (table6) reveals strong interdependent biogeochemical relationships across physical parameters, nutrients, and heavy metals within the evaluated soils: temperature exhibits a near-perfect positive correlation with Nickel ($r = 0.955$) and a strong positive association with Electrical Conductivity ($r = 0.721$), whereas moisture demonstrates significant positive correlations with pH ($r = 0.766$), Magnesium ($r = 0.699$), and Total Nitrogen ($r = 0.608$). Specific gravity correlates strongly and negatively with moisture ($r = -0.870$), Soil Organic Matter ($r = -0.633$), Total Organic Carbon ($r = -0.734$), and Copper ($r = -0.925$), but holds a strong positive relationship directly with Copper ($r = 0.910$). Total Organic Carbon shows prominent positive correlations with Bulk Density ($r = 0.703$), Zinc ($r = 0.802$), and Chromium ($r = 0.660$), while Cation Exchange Capacity displays a strong inverse relationship with Bulk Density ($r = -0.864$) and Chromium ($r = -0.753$). Furthermore, nutrient and trace metal dynamics are characterized by robust positive

interactions between Total Nitrogen and Magnesium ($r = 0.722$), Available Phosphorus and Zinc ($r = 0.713$), as well as Zinc and Magnesium ($r = 0.710$).

CONCLUSION

This study evaluated the physicochemical properties and heavy metal profiles of Fadama and Non-Fadama soils in Kubwa, Bwari and Ushafa, FCT Abuja. The coarse-textured, sand-dominated soils (49.31% - 90.00%) showed favorable baseline pH (5.7–6.9), non-saline electrical conductivity ($<228.0 \mu\text{S}/\text{cm}$), and strong Cation Exchange Capacity (17.81–21.55 $\text{cmol}(+)/\text{kg}$), with heavy metal levels remaining safely within WHO/FAO limits. However, severe lowland compaction (bulk density up to $1.81 \text{ g}/\text{cm}^3$) and critical phosphorus deficiency (0.14–1.46 mg/kg) present major agronomic constraints. Potential interventions of sustainable soil management must prioritize root-zone phosphorus banding, mechanical sub soiling, conservation tillage, and routine trace metal monitoring in some of the site with acute deficiency.

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