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Effects of Selected Soil Properties on the Chemical Speciation of Heavy Metals in Oghara, Delta State, Nigeria

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ABSTRACT

This study investigated the relationship between soil physicochemical properties and heavy metal speciation in soils from Oghara, Delta State, Nigeria. Surface soil samples (0–20 cm) were collected from ten sampling locations and analysed using standard analytical procedures. Heavy metal speciation was determined using the five-step sequential extraction method, while Fe, Zn, Cu, Cr, Ni, Pb, and Mn were quantified by Atomic Absorption Spectrophotometry (AAS). Pearson correlation analysis was employed to evaluate the relationships between soil particle-size fractions and heavy metal speciation. The soils were slightly acidic (pH 6.4 ± 0.1) and predominantly sandy (61.28%), with low organic matter (1.55 ± 0.03%) and cation exchange capacity (3.99 ± 0.05 cmol(+) kg^{-1}). Zinc (230.79 ± 0.20 mg kg^{-1}) and nickel (141.15 ± 0.10 mg kg^{-1}) recorded the highest total concentrations. Zinc occurred mainly in the Fe–Mn oxide-bound and organic matter-bound fractions, whereas nickel was predominantly associated with the residual fraction. Significant correlations ($p < 0.001$) between soil particle-size fractions and heavy metal forms indicated that soil texture strongly influenced metal distribution and retention. The study concludes that soil physicochemical properties, particularly particle-size distribution, play a significant role in controlling heavy metal speciation and potential mobility in Oghara soils. These findings provide baseline information for environmental monitoring, ecological risk assessment, and sustainable soil management.

KEYWORDS: Heavy metal speciation; soil physicochemical properties; sequential extraction; soil texture; Oghara; Niger Delta.

1. INTRODUCTION

Soil is a critical environmental resource that supports agricultural productivity, nutrient cycling, water regulation, and ecosystem sustainability. However, rapid industrialization, urbanization, agricultural intensification, petroleum exploration, and indiscriminate waste disposal have increased heavy metal contamination of soils [1]. Because heavy metals are persistent and non-biodegradable, they accumulate in the environment and may enter the food chain, posing significant ecological and public health risks [1].

Environmental risk associated with heavy metals depends not only on their total concentrations but also on their chemical forms (speciation), which determine their mobility, bioavailability, and toxicity. Consequently, heavy metal speciation has become an important approach for evaluating contaminant behaviour in soils [2]. The distribution of metals among geochemical fractions is strongly influenced by soil physicochemical properties such as pH, organic matter, cation exchange capacity, electrical conductivity, and soil texture, all of which regulate metal adsorption, retention, and release under changing environmental conditions [3].

Previous studies in the Niger Delta have largely focused on determining total heavy metal concentrations in soils, sediments, and water bodies, providing limited information on the relationships between soil physicochemical properties and heavy metal speciation[4], [5], [6]. As a result, the factors controlling heavy metal mobility and potential ecological risks in many locations remain insufficiently understood. Oghara, Delta State, is characterised by expanding residential development, agricultural activities, transportation, and proximity to petroleum-producing communities, all of which may influence soil quality and heavy metal dynamics. Despite these environmental pressures, information on the relationship between soil physicochemical properties and heavy metal speciation in Oghara soils is scarce.This study therefore investigated the relationship between selected soil physicochemical properties and heavy metal speciation in soils from Oghara, Delta State, Nigeria. The findings will improve understanding of heavy metal mobility and bioavailability and provide scientific evidence to support environmental monitoring, ecological risk assessment, and sustainable soil management in the study area.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Oghara, Ethiope West Local Government Area, Delta State, Nigeria (5°55′–5°59′ N, 5°40′–5°46′ E). The area has a humid tropical climate with annual rainfall of 2,000–2,500 mm and mean temperatures of 27–32 °C. It is underlain by the Benin Formation, with predominantly sandy loam soils. Agriculture, residential development, commercial activities, transportation, and proximity to petroleum-related operations constitute potential sources of heavy metal contamination.

2.2 Soil Sampling

Surface soil samples (0–20 cm) were collected from selected locations representing different anthropogenic activities using a stainless-steel auger. Five subsamples from each location were composited to obtain representative samples. Samples were air-dried, sieved (<2 mm) for physicochemical analyses, and further ground (<0.15 mm) for heavy metal determination.

2.3 Soil Physicochemical Analysis

Soil pH, electrical conductivity (EC), particle size distribution, organic carbon, organic matter, cation exchange capacity (CEC), moisture content, available phosphorus, and total nitrogen were determined using standard analytical procedures[7], [8], [9]

2.4 Heavy Metal Speciation and Determination

Heavy metal speciation was performed using the five-step sequential extraction procedure of [10], which fractionates metals into exchangeable, carbonate-bound, Fe–Mn oxide-bound, organic matter-bound, and residual forms. Concentrations of Cd, Pb, Cu, Zn, Cr, Ni, Fe, and Mn in each fraction were determined using Atomic Absorption Spectrophotometer (AAS)Labnicsmodel 2000

2.5 Quality Assurance and Data Analysis

Analytical quality was assured through the use of acid-washed glassware, analytical-grade reagents, procedural blanks, duplicate analyses, certified reference materials, and recovery tests. Data were analysed using descriptive statistics and Pearson's correlation to evaluate relationships between soil physicochemical properties and heavy metal speciation at a 95% confidence level.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Physicochemical properties of soil samples

Table 1. *Physicochemical properties of soil samples collected from Oghara, Delta State, Nigeria*

Parameter	Value
Available phosphorus (mg kg^{-1})	14.5 ± 0.1
Calcium (cmol(+) kg^{-1})	3.10 ± 0.02
Cation exchange capacity, CEC (cmol(+) kg^{-1})	3.99 ± 0.05
Clay (%)	9.29
Magnesium (cmol(+) kg^{-1})	0.52 ± 0.04
Organic matter (%)	1.55 ± 0.03
pH	6.4 ± 0.1
Potassium (cmol(+) kg^{-1})	0.05 ± 0.001
Sand (%)	61.28
Silt (%)	29.43
Sodium (cmol(+) kg^{-1})	0.32 ± 0.01
Total nitrogen (%)	0.11 ± 0.05

Values are expressed as mean ± standard deviation (SD)

Table 1 presents the physicochemical properties of soils collected from Oghara, Delta State. The soils were slightly acidic (pH 6.4 ± 0.1) and sandy in texture, comprising 61.28% sand, 29.43% silt, and 9.29%

clay. Organic matter, total nitrogen, and available phosphorus contents were 1.55 ± 0.03%, 0.11 ± 0.05%, and 14.5 ± 0.1 mg kg^{-1}, respectively. The cation exchange capacity was 3.99 ± 0.05 cmol(+) kg^{-1}, with calcium being the dominant exchangeable base (3.10 ± 0.02 cmol(+) kg^{-1}), followed by magnesium, sodium, and potassium.

3.1.2 Heavy metal speciation and total concentrations in soil samples

Table 2. *Heavy metal speciation and total concentrations in soil samples from Oghara, Delta State, Nigeria*.

Metal	Total (mg kg^{-1})	Exchangeable	Carbonate-bound	Fe–Mn oxide-bound	Organic matter-bound	Residual
Fe	12.36 ± 0.01	3.47 ± 0.01	3.28 ± 0.01	3.91 ± 0.01	1.70 ± 0.01	ND
Zn	230.79 ± 0.20	36.61 ± 1.00	35.96 ± 1.00	78.46 ± 1.60	77.48 ± 1.60	1.96 ± 0.06
Cu	0.95 ± 0.01	ND	ND	ND	0.63 ± 0.02	0.31 ± 0.01
Cr	4.94 ± 0.03	ND	ND	1.56 ± 0.10	2.60 ± 0.20	**0.78 ± 0.05**
Ni	141.15 ± 0.10	5.87 ± 0.30	4.99 ± 0.30	1.17 ± 0.10	51.07 ± 1.20	**78.05 ± 1.70**
Pb	9.05 ± 0.02	ND	ND	4.79 ± 0.20	ND	4.26 ± 0.20
Mn	11.26 ± 1.04	ND	8.24 ± 0.30	0.55 ± 0.02	ND	**2.47 ± 0.12**

Values are presented as mean ± standard deviation (SD) of triplicate determinations (n = 3). ND = Not detected (below the limit of detection)

Table 2 presents the total concentrations and geochemical fractions of heavy metals in soils from Oghara. Zinc recorded the highest total concentration (230.79 ± 0.20 mg kg^{-1}), followed by nickel (141.15 ± 0.10 mg kg^{-1}), whereas copper had the lowest concentration (0.95 ± 0.01 mg kg^{-1}). Iron occurred mainly in the exchangeable, carbonate-bound, Fe–Mn oxide-bound and organic matter-bound fractions, while zinc was predominantly associated with the Fe–Mn oxide-bound and organic matter-bound fractions. Nickel was largely concentrated in the residual and organic matter-bound fractions, whereas lead was detected only in the Fe–Mn oxide-bound and residual fractions. Copper and chromium were primarily associated with the organic matter-bound and residual fractions, while manganese occurred mainly in the carbonate-bound fraction

3.1.3 Heavy Metal Fractions and Soil Particle-Size Fractions In Soils.

Table 3. *Pearson correlation coefficients (r) between heavy metal fractions and soil particle-size fractions in soils in Oghara, Delta State, Nigeria*

Metal	Fraction	Clay	Sand
Iron (Fe)	Exchangeable	0.655	0.596
	Carbonate-bound	0.000	0.000
	Fe–Mn oxide-bound	0.217	.512
	Organic matter-bound	–0.143	–0.197
	Residual	0.645	–0.115
Zinc (Zn)	Exchangeable	0.466	0.565
	Carbonate-bound	0.818	0.738
	Fe–Mn oxide-bound	0.327	0.693
	Organic matter-bound	–0.436	0.784
	Residual	0.393	–0.813
Lead (Pb)	Exchangeable	0.000	0.000
	Carbonate-bound	0.000	0.000
	Fe–Mn oxide-bound	NC	0.776
	Organic matter-bound	0.000	0.000
	Residual	–0.782	–0.393

Table 3 shows significant correlations between soil particle-size fractions and heavy metal speciation ($p < 0.001$). Iron exhibited moderate positive correlations between its exchangeable and residual fractions and clay, whereas zinc showed strong positive correlations in the carbonate-bound fraction with clay ($r = 0.818$) and the organic-bound fraction with sand ($r = 0.784$). In contrast, the residual fractions of zinc ($r = –0.813$) and lead ($r = –0.782$) were negatively correlated with sand and clay, respectively. These findings indicate that soil texture significantly influences the distribution and retention of heavy metals in Oghara soils.

3.2 Discussion

The physicochemical properties of the Oghara soils showed that they were slightly acidic (pH 6.4), sandy in texture, and contained relatively low organic matter and cation exchange capacity (CEC). These characteristics suggest a moderate capacity for heavy metal retention and increased susceptibility to metal mobility. Soil pH, texture, organic matter, and CEC are widely recognized as the primary factors controlling the adsorption, mobility, and bioavailability of heavy metals in soils. Clay- and organic matter-rich soils generally retain metals more effectively than sandy soils because of their greater surface area and higher cation exchange capacity [11], [12]. In the Oghara samples, however, the prevalence of a sandy texture and low organic matter content likely limits the formation of stable metal-organic complexes and insoluble precipitates, thereby increasing the risk of heavy metal leaching into groundwater [13], [14].

The heavy metal speciation results revealed that zinc and nickel had the highest total concentrations, while copper occurred at the lowest concentration. Zinc was mainly associated with the Fe–Mn oxide-bound and organic matter-bound fractions, whereas nickel was predominantly present in the residual fraction. This distribution indicates that a substantial proportion of these metals occurs in relatively stable forms with lower immediate bioavailability. Previous studies have similarly reported that Fe–Mn oxides, soil organic matter, and residual mineral fractions serve as important sinks for heavy metals, thereby reducing their mobility under stable environmental conditions [15], [16], [17].

The correlation analysis further demonstrated significant relationships between soil texture and heavy metal fractions. The positive correlations of several iron and zinc fractions with clay indicate that clay minerals enhance heavy metal adsorption and retention [18]. Conversely, the negative correlations observed for the residual fractions of zinc and lead with sand suggest that coarse-textured soils have a lower capacity to retain metals, thereby increasing their potential mobility. These findings are consistent with previous reports that clay-rich soils immobilize heavy metals more effectively than sandy soils because of their larger surface area and greater adsorption capacity[19], [20], [21].

4. CONCLUSION

The study demonstrated that soil physicochemical properties significantly influence heavy metal speciation in soils from Oghara, Delta State. The soils were slightly acidic and predominantly sandy, with zinc and nickel recording the highest total concentrations. Most heavy metals occurred in the Fe–Mn oxide-bound, organic matter-bound, and residual fractions, indicating differences in their mobility and bioavailability. Significant correlations between soil particle-size fractions and heavy metal forms confirmed that soil texture plays an important role in controlling metal distribution. These findings provide baseline information for environmental monitoring, ecological risk assessment, and the sustainable management of contaminated soils in the Niger Delta.

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