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Impact of Palm Oil Mill Wastes on Soil Physicochemical Properties and Heavy Metal Concentration in Aguata Area, Anambra State, Nigeria

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ABSTRACT **Original research paper**

Palm oil mill wastes (POMWs), including palm oil mill effluent (POME), palm fruit fibre (PFF), and palm kernel shell (PKS), are major by-products of palm oil processing and are often discarded without proper treatment. This study evaluated the effects of these waste types on selected soil physical and chemical properties, and concentrations of bioavailable heavy metals (Cr, Pb, Zn, Cd) in Aguata Area, Anambra State, Nigeria. Soil samples were collected from three dumpsites and control sites across three depths (0–15 cm, 15–30 cm, and 30–45 cm). Standard laboratory protocols were employed, and data were analysed using ANOVA.

Results showed that POME-treated soils had significantly lower clay content (20.8%) and higher porosity (53.9%) at the surface layer compared to PKS and PFF. POME also increased soil pH (6.84), organic carbon (2.54%), total nitrogen (0.22%), and exchangeable base cations more than other treatments. Heavy metal concentrations, particularly Pb (0.19 mg/kg) and Zn (0.50 mg/kg), were higher in POME-affected soils but remained within permissible limits. Overall, POME demonstrated the greatest potential for improving soil fertility, though with elevated environmental risks due to heavy metal buildup. These findings underscore the need for regulated application and pre-treatment of POMWs to optimize their benefits while minimizing ecological risks in agroecosystems.

Keywords: Palm oil mill wastes (POMW), Soil fertility, Palm oil mill effluent (POME), Palm fruit fibre (PFF), Palm kernel shell (PKS), Bioavailable heavy metals, Soil physical and chemical properties.

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Introduction

The palm oil industry is a major agro-based enterprise in Nigeria, especially in the humid forest region where oil palm (*Elaeisguineensis*) trees grow both naturally and under cultivation. Among its numerous products, palm oil is widely consumed locally and internationally. It holds substantial domestic and industrial significance, with its production in Nigeria increasing annually (Nneli, 2014; Poku, 2002, 2017). In 2023, palm oil production in Nigeria reached 1.4 million metric tons (Sasu, 2023). This upward trend has remained consistent, with notable growth since 2010, positioning Nigeria among the leading global producers of palm oil (FAO, 2022). Palm oil extraction involves extensive water use. For every ton of crude palm oil (CPO) produced, approximately 5–7.5 tons of water are required—over half of which becomes palm oil mill effluent (POME) (Ma, 2000, Nwoko *et al.*, 2010). In addition to POME, solid wastes generated during processing include empty fruit bunches (EFB), palm fruit fibre (PFF), and palm kernel shells (PKS). These by-products are often discarded within and around processing facilities, leading to waste accumulation. When applied or indirectly deposited on soil, they can significantly influence its properties. For instance, they are known to improve soil structure and enhance water-holding capacity (Osubor & Oikeh, 2013; Yi *et al.*, 2019).

Palm oil mill wastes are rich in nutrients such as nitrogen, phosphorus, potassium, and magnesium, which can enhance soil fertility upon decomposition (Bakar *et al.*, 2015;Ermadani *et al*., 2019; Sitanggang *et al*., 2021). Organic waste application improves soil structure, helps mitigate land degradation, and preserves soil fertility—essential for sustainable agriculture. Additionally, the use of organic waste promotes the recycling of agricultural by-products, reducing the environmental burden of waste dumping and the over-reliance on chemical fertilizers, which may lead to soil and water contamination if misused (Ermadani *et al*., 2019, Sitanggang *et al*., 2021). For example, empty fruit bunches (EFB) release considerable amounts of potassium and nitrogen into the soil upon decomposition (Suhaimi & Ong, 2010; Teo *et al*., 2010). They can also influence soil pH, increase organic matter content, and stimulate microbial and enzymatic activity (Lim & Zaharah, 2000; Teo *et al*., 2010; Rashid *et al*., 2016; Teoh *et al*., 2020). While solid waste products like palm fruit fibre (PFF) and palm kernel shells (PKS) may be reused as fuel or mulch, POME is often discharged into the environment with little to no treatment (Olabode & George, 2020). The management of POME has been a major environmental concern due to its high organic content, biological oxygen demand (BOD), and phytotoxic components (Nwoko & Ogunyemi, 2010; Olabode & George, 2020). In many developing countries, poor enforcement of effluent discharge regulations has led to widespread environmental contamination (Ibrahim *et al*., 2019, Rupani & Sigh, 2010). POME is frequently released into water bodies, soil, or shallow evaporation ponds, posing significant risks to aquatic and terrestrial ecosystems (Rupani & Singh, 2010; Ibrahim *et al*., 2012; Loh *et al*., 2013). Soil exposed to fresh POME discharge often exhibits reduced microbial populations and diversity (Cheah *et al*., 2023, Okwute & Isu, 2020, Zainal *et al*., 2017).

Although various studies have focused on the influence of POME on soil, there is limited information on the effects of PFF and PKS, especially in Southeastern Nigeria. Aguata, a region with a strong palm oil production base, lacks specific data on how this waste products impact soil health (Aguata Local Government Agricultural Extension**,** 2023). This gap limits the development of environmentally sustainable waste management and agricultural practices. The main objective of this study is to evaluate the impact of palm oil mill wastes—Palm Oil Mill Effluent (POME), Palm Fruit Fibre (PFF), and Palm Kernel Shells (PKS)—on selected physical properties, and heavy metal concentrations in soils of Aguata, Anambra State, Nigeria. The specific objectives were to assessto evaluate the effects of POME, PFF, and PKS on soil physical properties (bulk density, porosity, texture, water-filled pore space) at varying depths and determine the concentrations of bioavailable heavy metals (Cr^{6+}, Pb^{2+}, Cd^{2+}, and Zn^{2+}) in soils exposed to palm oil mill wastes relative to uncontaminated control sites.

Materials and Methods

Study Area

The study was conducted at three oil palm waste dumpsites located in the Aguata area of Aguata Local Government Area, Anambra State, Nigeria. Aguata lies within the humid tropical rainforest zone of Southeastern Nigeria and is characterized by an annual rainfall ranging from 1,800 mm to 2,200 mm and a mean annual temperature ranging from 26°C to 36°C. The area experiences two distinct seasons: a rainy season from April to October and a dry season from November to March (NIMET, 2024). The predominant soil type is sandy loam, derived from false-bedded sandstone formations. These soils are moderately to poorly drained, especially in depressions and valley bottoms (Orajaka, 1975).
Three active palm oil processing sites were selected, each containing accumulated palm oil mill waste—Palm Oil Mill Effluent (POME), Palm Fruit Fibre (PFF), and Palm Kernel Shells (PKS). Each site was geo-referenced using a handheld GPS device and the coordinates are presented in Table 1. A control site, located 30 meters away from the waste dumpsites and with no visible waste contamination, was also selected for comparison.

Soil Sampling

Soil samples were collected from the three palm oil waste dumpsites (Table 1). At each dumpsite, soil was sampled from three depths: 0–15 cm, 15–30 cm, and 30–45 cm. Sampling tools included a soil auger, core sampler, perforated plastic plates (for proper aeration of samples intended for microbial analysis), and sterile nylon bags. For each dump, samples were taken from the centre and four cardinal points.

Table 1. The Name and Location of the Milling sites with its GPS Coordinates.

Location	Latitude	Longitude	Altitude
Ula	N 6°00’5.43708”	E 7°05’1.84236”	305.41 m
Eziagulu	N 6°00’7.95924”	E 7°04’24.86748”	300.84 m
Agba	N 6°01’15.31884”	E 7°04’39.82404”	301.75 m

Spot X: POME discharge point, Spot Y: Dump site of PFF, Spot Z: Dump site of PKS
At each spot (X, Y, Z), three samples were collected from three depths, designated as:
X1, X2, X3 (POME at depths 0–15, 15–30, 30–45 cm), Y1, Y2, Y3 (PFF at same depths)
Z1, Z2, Z3 (PKS at same depths), Samples were then grouped by depth: Sample A = (X1 + Y1 + Z1): 0–15 cm, Sample B =

(X2 + Y2 + Z2): 15–30 cm, Sample C = (X3 + Y3 + Z3): 30–45 cm.

Control samples were collected from the corresponding depths at 30 meters away and labelled D1, D2, and D3, respectively. Core samples were collected using core samplers at each depth for the determination of bulk density and related hydrologic properties. All samples were securely sealed in clearly labelled cellophane bags to avoid cross-contamination.

Laboratory Analysis:

Particle size distribution analysis was determined using the Bouyoucos hydrometer method (Day, 1965). Bulk density (BD) was calculated by measuring the mass of soil per unit volume, typically expressed in grams per cubic centimetre (g/cm^3) or kilograms per cubic meter (kg/m^3). The formula: BD=M/V where: BD = Bulk Density (in g/cm^3): where

M = Mass of the soil core (in grams), V = Volume of the soil core (in cubic centimetres) as described by Topp & Ferré, (2002). Water-Filled Pore Spaces (WFPS): Water filled pore space was derived from the bulk density (g/cm^3) as follows: WFPS = (Gravimetric water content / (Particle density - Bulk density)) x 100 (Linn & Doran, 1984).

Soil pH: soil pH was determined using a pH meter in 1:2.5 soils to water ratio (W/V) with a glass electrode as described by Unimke *et al.* (2014). Soil organic carbon (SOC) was determined by Walkley-Black wet oxidation method based on the oxidation of organic matter in soil by a mixture of potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) under acidic conditions. (Walkley & Black., 1934). Total nitrogen was determined by the micro- Kjeldahl digestion method (Bremner & Mulvaney, 1982; Pontes *et al.*, 2009). Available phosphorus was determined using the Bray P-1 method (Bray & Kurtz, 1945)

Exchangeable cations were extracted with 1 N NH4OAC at pH 7. For Calcium and magnesium, atomic absorption spectrophotometry (AAS) was used, while potassium and sodium were determined using flame photometer (Singh *et al.*, 2005). Exchangeable acidity (A+ and H+) was obtained by leaching the soil with IN KCl solution, and the extract titrated with standard NaOH as described by (Dai & Richter, 2000). Cation exchange capacity was determined by 1N-NH_4OAc method (Blackmore, *et al.*, 1987). Percentage base saturation was calculated by dividing the total exchangeable bases by exchangeable cation capacity (CEC) and multiplying by 100 (Blackmore, *et al.*, 1987). $\%\,\text{base saturation} = \frac{\text{Summation of exchanageable bases}}{\text{cation exchange capacity}} x\ 100.$ Heavy Metals (Cr^{6+}, Pb^{2+}, Cd^{2+}, Zn^{2+}) bioavailable forms were extracted using the DTPA method (Jaafar *et al.*, 2019) and concentrations were measured using Atomic Absorption Spectrophotometry (AAS).

Statistical Analysis

Data were analysed using GenStat 4th Edition. One-way analysis of variance (ANOVA) was used to assess variations in soil properties across different depths and waste types. Where significant differences were observed, mean separation was conducted using the Least Significant Difference (LSD) test at $p < 0.05$.

Result and Discussion

Effect of Palm Oil Mill Wastes on Selected Soil Physical Properties

The effect of palm oil mill wastes on selected physical properties—namely particle size distribution, bulk density, total porosity, and water-filled pore space (WFPS)—was analysed across three depth intervals (0–15 cm, 15–30 cm, and 30–45 cm), as shown in Table 2. At the surface layer (0–15 cm), sand content showed no significant difference among the waste dump sites compared to the control. However, soils influenced by Palm Fruit Fibre (PFF) recorded the highest sand content (69.2%), whereas Palm Kernel Shell (PKS) dumpsites exhibited the lowest (65.7%). This observation may be due to the fibrous and porous nature of PFF, which facilitates enhanced water infiltration and the downward movement of finer particles such as silt and clay (Abdullah & Sulaim, 2013). Silt content followed a similar trend, with the Palm Oil Mill Effluent (POME) site recording the highest value (12%). In contrast, clay content was significantly higher in the control soils than in the waste-affected sites, with the POME site recording the lowest clay percentage (20.8%) at the 0–15 cm depth.

At greater depths (15–30 cm and 30–45 cm), sand and silt contents did not differ significantly across the sites. However, clay content increased with depth in all waste-treated plots, peaking at 45.5% in the PKS site at 30–45 cm. This increase is consistent with the findings of Njuikom-Djoumbi *et al.* (2024), who reported clay illuviation in soils influenced by long-term organic waste application.

Table 2: Impact of the palm oil mill wastes on soil physical properties

Type of POMW	Sand (%)	Silt (%)	Clay (%)	Bulk density(g/cm3)	Total porosity (%)	Water filled pores (%)
			0-15CM			
POME	67.20±9.80	12.00±1.63	20.80±7.71	1.06±0.15	0.60±0.06	55.11±2.91

PFF	69.20±4.32	8.00±1.63	22.80±3.27	0.95±0.14	0.64±0.05	67.72±10.41
PKS	65.87±6.60	7.34±0.95	26.80±5.89	1.34±0.09	0.49±0.03	54.73±1.15
CONTROL	61.80±7.96	8.74±2.42	29.47±6.18	1.39±0.15	0.48±0.06	54.75±1.16
LSD (0.05)	Ns	Ns	7.30	Ns	Ns	Ns
			15-30cm			
POME	66.60±8.11	7.33±1.89	26.07±9.03	1.33±0.23	0.50±0.09	50.37±3.48
PFF	63.87±9.29	6.00±1.63	30.13±7.72	1.39±0.13	0.48±0.05	59.60±11.54
PKS	50.53±1.89	6.00±0.00	43.47±1.89	1.40±0.05	0.47±0.02	52.61±2.33
CONTROL	50.47±1.79	6.03±0.05	43.50±1.84	1.47±0.14	0.45±0.05	49.15±2.58
LSD (0.05)	14.92	Ns	13.10	Ns	Ns	Ns
			30-45cm			
POME	63.33±10.33	8.73±3.72	27.93±11.94	1.36±0.28	0.49±0.10	50.50±2.65
PFF	57.20±4.99	6.67±0.94	36.13+5.25	1.42±0.16	0.47±0.06	55.67±12.26
PKS	48.53±2.49	6.00±0.00	45.47±2.49	1.47±0.12	0.44±0.04	56.66±8.99
CONTROL	49.20±0.94	8.67±3.77	42.13+2.83	1.54±0.12	0.42±0.05	56.53±9.03
LSD (0.05)	Ns	Ns	13.73	Ns	Ns	Ns

LSD= Least Significant Difference at p<0.05 probability; NS= Not significantly different; POMW=Palm Oil Mill Waste; PFF=palm fruit fibre; PKS=Palm Kernel Shell; POME=Palm Oil Mil Effluent

Bulk density did not vary significantly among the dumpsites ($p < 0.05$). Nevertheless, the PFF-treated soils showed the lowest bulk density (0.95 g/cm³), followed by POME (1.061 g/cm³), suggesting enhanced soil structure and aeration. The PKS-dumpsite recorded the highest bulk density (1.34 g/cm³) at the surface, likely due to compaction from its dense, coarse material. Across all sites, bulk density increased with depth, in line with natural soil compaction patterns (Hossain *et al.*, 2015; Seehusen *et al.*, 2021).

Total porosity was highest in PFF-treated soils at the surface (0–15 cm) and decreased with depth. Conversely, PKS-dump soils consistently recorded the lowest porosity across all layers. WFPS values did not significantly differ from the control; however, the highest WFPS (67.7%) was observed in surface soils under PFF treatment. This suggests that PFF enhances moisture retention, a vital trait for drought-prone or water-limited environments.

These findings highlight that: PFF improves soil structure and water retention. POME enhances aeration and reduces compaction. PKS may increase soil compaction and limit water availability.

Impact of Palm Oil Mill Wastes on Soil Chemical Properties

Table 3 presents the effects of different palm oil mill wastes (POME, PFF, and PKS) on chemical soil properties, including pH, organic carbon (OC), total nitrogen (TN), available phosphorus (P), base saturation, and exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^{+}).

Soil pH varied significantly ($p < 0.05$) from the control across all waste types and depths, except in the surface soils (0–15 cm) of the PKS-dumpsite. Generally, pH decreased with depth, indicating greater surface-level influence from the POMWs. Although the influence of POMWs on base saturation and exchangeable K^{+} was not statistically significant, slight variations were observed when compared to the control.

At the 0–15 cm depth, POME-treated soils recorded significantly higher ($p < 0.05$) values of OC, TN, available P, and exchangeable base cations, attributed to the high organic and nutrient content of POME (Rupani & Singh, 2010; Nnaji *et al.*, 2016). Although both PFF and PKS improved these parameters relative to the control, the differences were not statistically significant. The lower impact of PFF and PKS may be due to their high lignin content and slower decomposition rates (Singh *et al.*, 2010).

Cation Exchange Capacity (CEC) followed a similar pattern. POME-dumpsite soils had significantly higher CEC across all depths, followed by PKS. PFF-dumpsite soils recorded the lowest CEC, especially at the deeper layers. This trend aligns with Eze (2013) and Nnaji *et al.* (2016), who reported elevated CEC in soils amended with POME.

Table 3: Impact of selected palm oil mill wastes on soil chemical properties at various depths

		→ (%) ←		(mgh/Kg)	→		Cmol/kg	←		(%)
Type of POMW	pH (H2O)	O.C	T. N	P	$Ca2^{+}$	$Mg2^{+}$	K^{+}	Na^{+}	CEC	Base saturation
				0 – 15 cm						
POME	6.84±0.06	2.54±0.62	0.22±0.05	13.95±9.48	4.93±1.61	2.87±0.57	0.36±0.04	0.22±0.02	9.66±2.81	80.50±2.69
PFF	6.80±0.14	1.98±0.28	0.17±0.02	8.19±2.93	3.87±0.68	2.80±0.65	0.25±0.09	0.19±0.06	8.04±1.81	79.93±0.75
PKS	6.27±0.17	1.73±0.08	0.15±0.01	6.31±2.16	3.47±0.94	2.03±0.48	0.21±0.08	0.15±0.02	7.79±1.40	79.80±2.79
CONTROL	6.20±0.08	1.30±0.52	0.11±0.05	3.98±1.15	2.93+0.75	1.40±0.43	0.27±0.02	0.14±0.00	5.74±1.51	77.87±0.74
LSD (0.05)	0.53	0.84	0.07	9.20	1.41	0.99	NS	NS	3.16	2.99
				15 – 30 cm						
POME	6.83±0.12	1.76±1.00	0.15±0.09	11.40±9.42	2.93±0.82	2.13±0.82	0.20±0.05	0.15±0.02	6.91±1.81	77.53±2.85
PFF	6.70±0.22	1.02±0.37	0.09±0.03	4.83±2.18	2.33±0.46	1.60±0.31	0.22±0.04	0.12±0.03	5.81±0.90	73.00±4.61
PKS	6.33±0.19	0.75±0.19	0.06±0.02	3.47±2.31	2.47±0.34	1.60±0.33	0.17±0.03	0.12±0.02	5.36±0.69	81.10±2.62
CONTROL	5.90±0.22	0.49±0.19	0.04±0.02	1.83±0.32	2.07±0.41	1.33±0.19	0.17±0.03	0.12±0.02	4.79±0.68	76.70±3.61
LSD (0.05)	0.48	1.05	0.09	NS	NS	NS	NS	NS	2.03	NS
				30 – 45 cm						
POME	6.66±0.33	4.62±4.28	0.11±0.10	8.15±7.40	2.40±0.57	1.93±0.62	0.16±0.08	0.18±0.02	6.04±1.60	77.20±4.95
PFF	6.37±0.42	0.46±0.22	0.05±0.01	3.56±1.29	1.87±0.19	1.13±0.25	0.18±0.05	0.14±0.06	4.19±0.54	79.03±3.95
PKS	5.87±0.38	0.56±0.24	0.05±0.02	2.71±1.40	1.87±0.19	1.40±0.16	0.23±0.03	0.15±0.05	4.41±0.40	72.53±15.13
CONTROL	5.70±0.36	3.76±4.77	0.03±0.01	1.70±0.36	1.60±0.33	1.13±0.25	0.20±0.05	0.11±0.03	4.25±0.67	71.53±8.06
LSD (0.05)	0.57	NS	NS	NS	0.67	0.64	NS	NS	1.47	2.98

LSD= Least Significant Difference at $p<0.05$ probability; NS= Not significantly different; POMW=Palm Oil Mill Waste; PFF=palm fruit fibre; PKS=Palm Kernel Shell; POME=Palm Oil Mil Effluent

At 0–15 cm, POME-dumpsite soils had the highest concentrations of: Ca^{2+}: 4.93 cmol/kg, Mg^{2+}: 2.87 cmol/kg, Na^{+}: 0.22 cmol/kg and CEC: 9.66 cmol/kg. These were significantly higher than those of the control and other treatments. PKS sites showed moderate increases, while PFF had the lowest K^{+} and Na^{+} concentrations at 30–45 cm, likely due to slower mineralization and reduced nutrient release. In summary, these results suggest that: POME significantly enhances soil pH, OC, nutrient levels, and CEC. PKS has moderate potential, especially for deeper nutrient retention. PFF shows limited chemical improvement capacity. The decline in nutrient concentrations with depth emphasizes the effectiveness of surface application for maximum benefit. These findings confirm **POME** as a potent organic amendment for improving acidic and nutrient-deficient soils (Agamuthu *et al*., 1986; Ramadhan *et al*., 2021).

Effect of Palm Oil Mill Waste on Bioavailable Heavy Metals

Table 4 presents the bioavailable concentrations of selected heavy metals—Chromium (Cr^{2+}), Lead (Pb^{2+}), Zinc (Zn^{2+}), and Cadmium (Cd^{2+})—across the different dumpsites. At 0–15 cm, the concentration of Cr^{2+} differed significantly ($p<0.05$) in POME soils compared to the control. Zn^{2+} and Cd^{2+} were significantly elevated in both POME and PFF soils relative to the control, while PKS showed no significant difference. Pb^{2+} was significantly higher in POME soils across all depths when compared to the control. At deeper depths (15–30 cm and 30–45 cm), only POME soils maintained significantly higher Zn^{2+} and Cd^{2+} levels. Cr^{2+} and Pb^{2+} concentrations declined with increasing depth across all treatments, indicating limited mobility but potential surface accumulation. The significantly higher Pb^{2+} values in POME-impacted soils highlight a possible accumulation risk, particularly with continuous or large-scale application. This is consistent with the findings of Nnaji *et al*. (2016), who noted long-term buildup of heavy metals in organically amended soils. These results suggest that POME poses the highest risk of heavy metal accumulation, especially Pb^{2+}., PFF may contribute to elevated Zn^{2+} and Cd^{2+} at surface levels and PKS showed the lowest impact on heavy metal content. Given the potential for long-term toxicity and environmental contamination, periodic monitoring and controlled application of POMWs are essential to avoid exceeding permissible thresholds for heavy metals in agricultural soils.

Table 4: Impact of palm oil mill waste types (POMW) on the selected bioavailable heavy metals

		mg/kg		
Type of POMW	Cr^{2+}	Pb^{2+}	Zn^{2+}	Cd^{2+}

		0 – 15 cm		
POME	0.41+0.01	0.19+0.03	0.50+0.11	0.56+0.13
PFF	0.26+0.03	0.12+0.02	0.38+0.06	0.44+0.15
PKS	0.24+0.05	0.04+0.04	0.17+0.03	0.25+0.13
CONTROL	0.21+0.02	0.04+0.03	0.15+0.04	0.30+0.08
LSD (0.05)	0.09	NS	0.15	0.21
		15 – 30 cm		
POME	0.27+0.09	0.03+0.01	0.24+0.05	0.34+0.02
PFF	0.21+0.01	0.02+0.02	0.16+0.03	0.32+0.09
PKS	0.15+0.04	0.00+0.01	0.12+0.05	0.20+0.09
CONTROL	0.10+0.02	0.02+0.02	0.11+0.01	0.11+0.05
LSD (0.05)	0.08	NS	0.13	NS
		30 – 45 cm		
POME	0.20+0.07	0.00+0.00	0.16+0.04	0.21+0.01
PFF	0.12+0.05	0.01+0.01	0.07+0.03	0.11+0.08
PKS	0.13+0.04	0.00+0.00	0.07+0.02	0.08+0.08
CONTROL	0.11+0.03	0.00+0.00	0.07+0.03	0.14+0.09
LSD (0.05)	0.08	NS	0.08	NS

POMW =palm oil mill wastes; LSD=Least significant difference at P<0.05 probability; NS= Not significantly different; PFF=palm fruit fibre; PKS=Palm Kernel Shell; POME=Palm Oil Mil Effluent

Heavy Metal Concentrations and Environmental Risk Assessment

The concentrations of heavy metals—such as Cu, Zn, Fe, and Mn—were significantly higher in soils treated with POME and PFF compared to the control (Table 5). This suggests that POME, in particular, may contain higher levels of these metals or enhance their mobility through acidic or organic byproducts. While these metals are essential micronutrients at low concentrations, their accumulation can pose serious environmental risks, including: Soil toxicity and inhibition of beneficial microbial activity. Leaching into groundwater, leading to water quality deterioration. Bioaccumulation in crops, potentially affecting food safety and human/animal health (Okwute & Isu, 2020). The risk is especially concerning under long-term or excessive application of untreated POMW. Therefore, best management practices such as composting, controlled application, and regular monitoring of soil metal content are essential to reduce bioavailability and ensure ecological safety.

Conclusion

Palm oil mill wastes—particularly POME, PFF, and PKS—demonstrate considerable potential in improving soil physical properties (e.g., porosity, texture) and enhancing chemical fertility (e.g., organic carbon, nitrogen, phosphorus, and CEC). These benefits support sustainable land use, efficient recycling of agro-industrial byproducts, and environmental conservation. However, the increased levels of bioavailable heavy metals associated with especially POME application present environmental concerns. To maximize the agronomic benefits while minimizing ecological risks, integrated waste management approaches should be adopted. These include: composting of palm oil mill wastes before field application, Applying wastes at agronomically recommended rates, Routine soil and plant monitoring, and Continued research on best practices for land application. Through these strategies, palm oil mill wastes can be transformed into sustainable soil amendments that align with both productivity and environmental sustainability goals.

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