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Soil Quality Assessment Around Oil Palm Production Belts In Akwa-Ibom State, Southern Part Of Nigeria

Ogorure, D. A., Gobo, A.E., Youdeowei, P.O., Dollah, O.C.
Department Of Geology, Faculty Of Science, Rivers State University Nkporlu-Orowrukwo Port Harcourt, Rivers State, Nigeria.
Institute Of Geosciences And Environmental Management, Rivers State University Nkporlu-Orowrukwo Port Harcourt, Rivers State, Nigeria.

Abstract
This study looked into soil pollution resulting from oil palm production wastes in the oil palm production belts of Akwa-Ibom State. The study utilized the experimental research design. Soil samples were collect from both the POME impacted soils and the soils not impacted (control). These soil samples were sent to the laboratory for analysis. The Analysis of Variance test was used for data analysis. Data revealed differences in soil quality between the oil palm production sites and the control site. The content values of various parameters were higher than those recommended by the World Health Organization (WHO), which is attributed to the unregulated introduction of palm oil mill effluents (POME). The study found that the key soil quality parameters—including pH, cation exchange capacity (CEC), nitrogen (N), phosphorus (P), potassium (K), and heavy metals—showed significant differences from WHO standards. The study further highlighted a decrease in nitrogen, phosphorus, and potassium (NPK) in the sampled soils compared to the control soils. The study observed that soil organic carbon (SOC) increased in the sampled soils compared to the control soils, likely due to POME's effect in enhancing SOC depending on the quantity applied. Soil physical conditions, such as particle size composition (sand, silt, and clay), WHC, and bulk density, also increased in the sampled soils relative to the control site. The ANOVA results for the soil characteristics in Akwa-Ibom State were significantly different at p<0.05. This meant that there is a significant difference in the soil characteristics both at the palm oil polluted sites and the control area. The study recommended producing oil palm sustainably; the use of cleaner technologies for processing oil palm amongst others.

Keywords: *Soil-quality, Oil-palm, Soil-pollution, POME*

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I. Introduction

Nigeria is the fifth largest producer of oil palm globally (Shehu & Salleh, 2023). Its domestic production account for around 1.5% of the world's palm oil produce (Adikaibe et al, 2024). Oil palm industry has positive economic impacts, such as the creation of employment, income generation, and poverty reduction (Akeem et al., 2024); on the other hand, it also has significant environmental challenges (Edaba et al., 2023). The environmental implications associated with oil palm plantations range from pollution caused by waste discharge, emissions from farm operations, to deforestation, which has a ripple effect on biodiversity, climate change and soils (Yu et al., 2024). Additionally, oil palm cultivation, like other agricultural activities, leads to environmental emissions during its production, including bush burning and the use of pesticides like herbicides, insecticides, and fungicides (Nwogu et al., 2023). These agrochemicals often result in pollution, particularly when they reach waterways through soil erosion and water runoff (Mitra et al., 2024). Many synthetic pesticides are resistant to degradation, meaning they can persist in the environment for extended periods which leads to contamination of the ecosystems and posing risks to aquatic organisms and soil microbes (AbuQamar et al., 2024). When humans consume these contaminated organisms, it can lead to sub-lethal effects on health (Zhou et al., 2024).

The environment consist of both living and non-living things, and these are critical for sustaining life in the ecosystem (Venegas-Aravena & Cordaro, 2024). The quality of the environment directly impacts the health of all organisms, including humans (Shetty et al., 2023). Environmental health is the interrelationship between people and their environment, wherein human health and a balanced, non-polluted ecosystem are sustained or degraded (Sharma et al., 2023). Poor oil palm production practices contribute to environmental degradation, ultimately harming both the environment, soils and public health (Thompson-Morrison et al., 2023). The rapid growth in global demand for vegetable oil, including palm oil, has further exacerbated environmental pressures (Manorama et al., 2024). Global demand for vegetable oils increased from 100 million tons in 2005 to an estimated 150 million tons in 2020, driven by population growth and rising living standards in developing countries (Sibhatu, 2023). As the most affordable and versatile edible oil, palm oil plays an increasingly significant role in meeting this demand (Voora et al., 2023). However, its production comes at a cost. The expansion of oil palm plantations is a major driver of deforestation, leading to biodiversity loss, greenhouse gas emissions, soil contamination and land degradation (Erwiningsih, 2023). In some cases, it has also contributed to forest and peatland fires which exacerbates air and water pollution (Gómez et al., 2023).

Excessive exploitation of oil palm products can lead to uncontrolled pressure on the resource, threatening its long-term availability. Many indigenous communities are unaware of the risks posed by unsustainable harvesting practices, which could endanger the continued availability of oil palm products. Palm oil has become controversial, not only for health reasons but also for its environmental and social impacts. Palm oil plantations have been scrutinized for their role in destroying biodiverse rainforests, contributing to climate change, and displacing local communities whose traditional livelihoods are often disrupted (VanderWilde, 2023). The environmental degradation caused by oil palm production has far-reaching implications for human well-being, as the health of the environment is intrinsically linked to human health.

Despite these challenges, the oil palm industry has driven economic growth in Nigeria, particularly in rural areas (Shehu & Salleh, 2023). However, this growth has been accompanied by significant criticism due to the negative environmental and social effects of oil palm expansion (Olayide, O. E., & O'Reilly, 2024). In Nigeria's Niger Delta region, local communities have experienced conflicts over land as companies expand their plantations (Victor et al., 2024). While these communities may benefit from the economic boom brought about by oil palm, the social costs of land disputes and environmental degradation cannot be overlooked (Toumbourou & Dressler, 2024). Smallholder farmers, who cultivate around 50% of the global oil palm area, play a critical role in the industry. Their involvement has helped raise farm incomes and reduce poverty in regions like the Niger Delta (Berenschot et al., 2024). However, unsustainable production activities risk undermining these economic benefits by contributing to environmental harm (Kinseng et al., 2023). During mechanized farm operations, vehicular emissions release pollutants such as carbon oxides, nitrogen oxides, sulphur oxides, hydrogen sulphide, and suspended particulate matter, contaminating the surrounding environment. In addition to emissions from vehicles, oil palm processing activities also generate gaseous emissions. Semi-mechanized and smallholder mills, which dominate Nigeria's oil palm sector, release pollutants during processes like boiling and digestion, contributing to atmospheric pollution and soil deterioration (Odigie, 2024).

It is evident that oil palm cultivation plays a vital role in Nigeria's economy, particularly in the Niger Delta region, however, it also poses significant environmental challenges. Unsustainable production practices contribute to air, water, and soil pollution, deforestation, and greenhouse gas emissions, all of which have serious implications for human health and well-being. Addressing these issues requires a concerted effort to adopt more sustainable production practices, reduce waste and emissions, and mitigate the environmental impacts of oil palm cultivation. By doing so, Nigeria can continue to benefit economically from its oil palm industry while minimizing the environmental costs associated with its production. The current attempt is to assess soil characteristics around oil palm production belts in Akwa Ibom State, Southern parts of Nigeria.

II. Materials And Methods

Akwa Ibom, covering an area of 6,900 sq km, is situated between Cross River, Abia, and Rivers States, along the sandy coastal plain of the Gulf of Guinea (Umanah et al., 2023). Bordered to the south by the Atlantic Ocean, the coastline stretches from Ikot Abasi to Oron, offering breath-taking views of the ocean meeting the sky. Akwa Ibom lies between latitudes 4°32' and 5°33' North, and longitudes 7°25' and 8°25' East, forming a triangular shape that spans a total land area of 8,412 sq km (Awelewa & Ogban, 2015). The state encompasses the Qua Iboe River Basin, the western part of the lower Cross River Basin, and the eastern part of the Imo River Basin. Its 129-kilometer-long ocean front from Ikot Abasi to Oron is home to captivating coastal features, mangrove forests, and scenic sandy beach resorts (Etuk et at., 2020).

The state's physical relief is mostly flat, with some areas featuring valleys, creeks, and swamps due to the influence of the Atlantic Ocean, Qua Iboe River, and Cross River. Akwa Ibom experiences two main seasons: the rainy season from May to October, and the dry season from November to April (Okoro et al., 2015). However, coastal regions receive rainfall almost year-round. Harmattan winds blow from the northeast in December and early January (Jacob et al., 2022).

Akwa Ibom is location within the humid tropics, combined with its proximity to the sea, results in a tropical climate characterized by high humidity, abundant rainfall, and high temperatures (Famous, 2024). The state's average annual temperature ranges between 26°C and 29°C, with about 1,450 hours of sunshine per year. Rainfall varies from 2,000 mm to 3,000 mm annually, depending on the region. Maximum humidity occurs in July, while January records the lowest. The thick cumulonimbus clouds dominate the sky from March to November, with high evaporation levels ranging between 1,500 mm and 1,800 mm annually (Ushurhe et al., 2024).

The state's climate supports the cultivation of a variety of crops, including palm produce, rubber, cocoa, rice, cassava, yam, and maize (Weli et al., 2017). Agriculture is practiced in two main forms: small-scale peasant farming for local consumption and estate farming specializing in cash crops such as rubber, cocoa, rice, and oil palm. The abundance of palm produce attracts investments in oil palm processing industries. The poor handling of the process thus results in environmental pollution, soil inclusive.

The study utilized an experimental research design, with primary data collected through field surveys. These surveys included soil quality analysis conducted in selected oil palm production areas in Akwa Ibom State. The study focused on communities involved in oil palm production. A global positioning system (GPS) was employed to track the coordinates of oil palm production and milling sites.

Soil samples for quality analysis were collected using a point sampling method, where points were established around ten oil palm production sites (Nwagbara et al., 2017). These points were further expanded to five locations using a distance decay approach (Ozabor, 2014). This process was replicated at all selected oil palm production and control sites for consistent soil quality analysis. The geographic coordinates tracked during soil sampling were used for geo-rectifying the selected production sites. Soil samples were collected with a soil auger, stored in labelled polythene bags, and transported to a laboratory for various analyses (Famous & Adekunle, 2020).

A total of 60 soil samples were analysed in the lab for their physical, chemical, and heavy metal properties. The samples were air-dried, sieved through a 2mm mesh to remove debris, and ground into a powdery form using a ceramic mortar. These processed samples were stored in plastic containers until analysis. The physico-chemical and heavy metal properties analysed included sand, silt, clay, temperature, electrical conductivity (EC), water holding capacity (WHC), bulk density (BD), pH, soil organic carbon (SOC), cation exchange capacity (CEC), available phosphorus (P), total nitrogen (TN), potassium (K), lead (Pb), chromium (Cr), cadmium (Cd), iron (Fe), nickel (Ni), and zinc (Zn).

Both descriptive and inferential statistics were employed for data analysis, with results presented as means, standard deviations, and percentages. One-way Analysis of Variance (ANOVA) was used to assess differences and variances between and within study groups and variables (Ozabor & Wodu, 2016; Okumagba & Ozabor, 2016). This statistical method was selected due to its effectiveness in comparing variances. The analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 24.0.

III. Results And Discussion

Table 1 presents the data on the physical, chemical, and heavy metal properties of soils around oil palm production sites in Akwa Ibom State. The results from the control sites were used for comparison. The sand content (%) in the soil varied from 94.3% to 96.4%, with a mean of 95.09% in Esit Eket LGA; from 94.5% to 96.5%, with a mean of 95.44% in Ibesikpo LGA; and from 93.9% to 96.7%, with a mean of 95.34% in Nsit Ubium LGA. In contrast, the control site had a sand content of 89.5%. The highest silt content (6.2%) was recorded in the control site, while oil palm production sites had values ranging from 1.40% to 2.90%, with Nsit Ubium LGA showing the highest mean of 2.12%. Clay content also varied, with the control site showing the highest value of 4.3%, compared to mean values of 2.85% in Esit Eket LGA, 2.67% in Ibesikpo LGA, and 2.54% in Nsit Ubium LGA.

Soil temperature across the sampled sites in Akwa Ibom State ranged from 23.6°C to 28.6°C, while the control site recorded 27.5°C. The water holding capacity (WHC) of the sampled soils was higher than that of the control site, possibly due to the influence of palm oil mill effluents (POME). WHC values were 31.1% in Esit Eket LGA, 31.50% in Ibesikpo LGA, and 33.16% in Nsit Ubium LGA, compared to 22.9% in the control site. Bulk density (kg/m^3) was highest in Nsit Ubium (2.90 kg/m^3), followed by Ibesikpo (2.88 kg/m^3), while the control site had a lower value of 1.4 kg/m^3. The bulk density increase is attributed to POME, which adds bulk to the soil over time. The pH of the sampled soils was acidic, ranging from 4.90 to 5.50 in Esit Eket LGA, 4.91 to 5.62 in Ibesikpo LGA, and 4.87 to 5.66 in Nsit Ubium LGA, while the control site showed a less acidic pH of 5.9, which is closer to neutral and more conducive for plant growth.

Soil organic carbon (SOC) levels were higher in the sampled sites, with mean values of 5.01 mg/kg in Esit Eket LGA, 5.03 mg/kg in Ibesikpo LGA, and 5.14 mg/kg in Nsit Ubium LGA, compared to 3.6 mg/kg in the control site. The increase in SOC is likely due to POME from fresh fruit bunch (FFB) processing. Cation exchange capacity (CEC) was lower in the sampled soils, with values between 2.76 mg/kg and 3.20 mg/kg in Esit Eket LGA, 2.79 mg/kg and 3.24 mg/kg in Ibesikpo LGA, and 2.69 mg/kg and 3.18 mg/kg in Nsit Ubium LGA, compared to a higher mean of 6.4 mg/kg in the control site.

Nitrogen, phosphorus, and potassium levels were significantly lower in the sampled soils compared to the control site. The mean nitrogen content in Esit Eket LGA was 2.46 mg/kg, 2.29 mg/kg in Ibesikpo LGA, and 2.36 mg/kg in Nsit Ubium LGA, compared to 5.48 mg/kg in the control site. Phosphorus levels in the control soil were 18.4 mg/kg, while values in the sampled soils were 7.36 mg/kg in Esit Eket LGA, 6.95 mg/kg in Ibesikpo LGA, and 8.42 mg/kg in Nsit Ubium LGA. Similarly, potassium levels in the control site were 0.94 mg/kg, while the sampled soils ranged between 0.29 mg/kg and 0.74 mg/kg. This reduction is attributed to the unregulated application of POME, which, in controlled quantities, can act as a soil fertilizer.

The concentrations of heavy metals, including lead (Pb), chromium (Cr), cadmium (Cd), nickel (Ni), and zinc (Zn), were higher in the sampled sites compared to the control site. This is due to the presence of crude palm oil (CPO) residues from POME waste during FFB processing. For example, Pb levels ranged from 0.01 mg/kg to 0.06 mg/kg in the sampled soils, compared to 0.008 mg/kg in the control site; Cr levels ranged from 0.06 mg/kg to 0.21 mg/kg, compared to 0.001 mg/kg in the control site; and Ni levels ranged from 0.31 mg/kg to 0.63 mg/kg in the sampled soils, compared to 0.001 mg/kg in the control site.

However, higher iron (Fe) content was recorded in the sampled soils across the selected LGAs compared to the control soils. The Fe levels in the sampled soils ranged from 12,600 mg/kg to 14,800 mg/kg, while the control soils had a value of 12,800 mg/kg. In conclusion, soil properties in the areas affected by oil palm production have been influenced by crude palm oil activities. The higher sand content observed compared to the control sites may be due to the significant drainage of palm oil into the deeper soil layers, which may wash away nutrients and fine particles. This could also affect soil aeration due to the excess crude palm oil in the impacted soils.

Additionally, the study found that soils from oil palm production sites were more acidic, while the control soil showed pH levels closer to neutral. Increased soil acidity can hinder the activity of beneficial microorganisms, which are essential for maintaining soil health. The rise in soil organic carbon (SOC) is attributed to the introduction of palm oil mill effluents (POME) from crude palm oil processing. The chemical properties of the soil indicated a significant reduction in nutrients at the oil palm production sites, particularly nitrogen (N), phosphorus (P), and potassium (K), which are crucial for plant growth and development.

Lower NPK levels could negatively affect plant growth over time, as the activity of soil microbes has been diminished, reducing soil fertility. This decline in nutrient availability, especially nitrogen and phosphorus, is likely to impact plant growth. Therefore, intensive crude palm oil production may contribute to a gradual decline in soil quality by depleting essential nutrients and affecting overall soil health.

Table 1: Soil quality analysis as influenced by oil palm activities in sampled LGAs in Akwa Ibom State

		Esit Eket				**Ibesi kpo**				**Nsit Ubium**			
Parameters	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Control**
Sand (%)	94.30	96.40	95.09	0.73	94.50	96.50	95.44	0.73	93.90	96.70	95.34	0.88	89.5
Silt (%)	1.40	2.90	2.06	0.54	1.40	2.30	1.89	0.31	1.70	2.60	2.12	0.30	6.2
Clay (%)	2.20	3.90	2.85	0.62	2.10	3.40	2.67	0.46	1.40	3.50	2.54	0.64	4.3
Temp	23.60	28.90	25.74	1.72	25.10	28.60	26.44	1.03	23.70	26.40	24.58	0.96	27.5
WHC (%)	27.80	34.90	31.16	2.10	28.60	33.10	31.50	1.36	30.50	35.50	33.16	1.31	22.9
Bulk D (Kg/m^3)	2.60	3.10	2.78	0.15	2.60	3.20	2.88	0.20	2.20	2.90	2.54	0.28	1.4
Ph	4.79	5.50	5.13	0.27	4.91	5.62	5.23	0.23	4.87	5.66	5.26	0.26	5.9
SOC (mg/kg)	4.56	5.30	5.01	0.20	4.65	5.70	5.03	0.31	4.83	5.61	5.14	0.24	3.6
CEC (mg/kg)	2.76	3.20	3.00	0.14	2.79	3.24	2.98	0.14	2.69	3.18	2.97	0.16	6.4
N (mg/kg)	2.13	2.78	2.46	0.16	2.09	2.49	2.29	0.13	2.16	2.67	2.36	0.15	5.48
P (mg/kg)	6.52	8.41	7.36	0.61	5.93	7.56	6.95	0.42	7.61	9.09	8.42	0.47	18.4
K (mg/kg)	0.29	0.45	0.38	0.05	0.39	0.58	0.47	0.05	0.33	0.74	0.52	0.12	0.94
Pb (mg/kg)	0.01	0.05	0.03	0.01	0.01	0.06	0.03	0.01	0.01	0.05	0.03	0.01	0.008
Cr (mg/kg)	0.06	0.18	0.10	0.04	0.07	0.21	0.14	0.05	0.06	0.18	0.10	0.04	0.001
Cd (mg/kg)	0.21	0.34	0.27	0.04	0.19	0.35	0.27	0.04	0.21	0.34	0.27	0.04	0.0004
Fe (mg/kg)	13700	14775	14194.5	318.16	13800	14800	14231.4	341.8	12600	14100	13214	438.82	12800
Ni (mg/kg)	0.39	0.63	0.55	0.08	0.48	0.55	0.51	0.02	0.31	0.59	0.47	0.07	0.001
Zn (mg/kg)	2.70	4.20	3.44	0.50	3.30	4.20	3.65	0.27	2.90	3.70	3.28	0.26	1.42

***Min- Minimum; Max- Maximum; SD- Standard deviation**

Table 2: ANOVA summaries for soil characteristics in sampled sites in Akwa-Ibom State

	Esit Eket	**Ibesikpo**	**Nsit Ubium**	**Control**	**F**	**Sig**
Parameters	**Mean**	**Mean**	**Mean**	**Mean**		
Sand (%)	95.09	95.44	95.34	89.5	10.30	P<0.05
Silt (%)	2.06	1.89	2.12	6.2	11.21	P<0.05
Clay (%)	2.85	2.67	2.54	4.3	15.21	P<0.05
Temp	25.74	26.44	24.58	27.5	18.10	P<0.05
WHC (%)	31.16	31.50	33.16	22.9	08.10	P<0.05
Bulk D (Kg/m^3)	2.78	2.88	2.54	1.4	09.32	P<0.05
pH	5.13	5.23	5.26	5.9	07.18	P<0.05
SOC (mg/kg)	5.01	5.03	5.14	3.6	08.34	P<0.05
CEC (mg/kg)	3.00	2.98	2.97	6.4	13.01	P<0.05
N (mg/kg)	2.46	2.29	2.36	5.48	18.11	P<0.05
P (mg/kg)	7.36	6.95	8.42	18.4	11.34	P<0.05
K (mg/kg)	0.38	0.47	0.52	0.94	05.19	P<0.05
Pb (mg/kg)	0.03	0.03	0.03	0.008	14.01	P<0.05
Cr (mg/kg)	0.10	0.14	0.10	0.001	10.03	P<0.05
Cd (mg/kg)	0.27	0.27	0.27	0.0004	06.04	P<0.05
Fe (mg/kg)	14194.5	14231.4	13214	12800	12.16	P<0.05
Ni (mg/kg)	0.55	0.51	0.47	0.001	07.61	P<0.05
Zn (mg/kg)	3.44	3.65	3.28	1.42	08.01	P<0.05

Table 2 revealed the ANOVA results for the soil characteristics in Akwa-Ibom State. The reason for the comparison was to check for difference in the characteristics in soil quality across the sampled locations. In all the soil characteristic were significantly different at $p<0.05$. This meant that there is a significant difference in the soil characteristics both at the palm oil polluted sites and the control area.

The study's findings revealed notable differences in soil quality between the oil palm production sites and the control site. The content values of various parameters were higher than those recommended by the World Health Organization (WHO), which is attributed to the unregulated introduction of palm oil mill effluents (POME). While POME can serve as a beneficial fertilizer when applied in controlled quantities, excessive use has led to an increase in heavy metal concentrations—specifically lead (Pb), chromium (Cr), cadmium (Cd), nickel (Ni), and zinc (Zn)—in the sampled soils compared to the control soils. These elevated levels are due to the crude palm oil (CPO) residues present in the soils, originating from the improper disposal of POME and other solid and liquid wastes generated during the processing of fresh fruit bunches (FFB) into crude palm oil. Improper management of these wastes results in their contact with the soil, thereby affecting its quality over time.

Soil is a vital resource for supporting plant growth and development, and its degradation due to poorly managed oil palm production activities poses a serious concern. The study found that the key soil quality parameters—including pH, cation exchange capacity (CEC), nitrogen (N), phosphorus (P), potassium (K), and heavy metals—showed significant differences from WHO standards. Parameters such as water holding capacity (WHC), bulk density (BD), soil organic carbon (SOC), and heavy metals like Pb, Cr, and Ni were particularly affected in the oil palm production sites (Eyetan & Ozabor, 2021).

Similar studies, like Ogoro et al (2020), also reported increased heavy metal contents in soil due to oil palm activities, with levels exceeding WHO standards. The study further highlighted a decrease in nitrogen, phosphorus, and potassium (NPK) in the sampled soils compared to the control soils, aligning with findings by Nwaugo et al. (2024); Godspower et al. (2024), who observed that POME has a direct impact on soil quality, particularly in reducing nitrogen and phosphate content as POME quantities increase. Ushurhe et al. (2024) also noted that POME lowers nitrogen levels in tested soils compared to soils without POME. These studies support the conclusion that unregulated POME from oil palm activities has negatively impacted soil quality in the study area.

Additionally, Ozabor et al. (2024) found that untreated POME discharged into the environment significantly affected both soil and water quality. Similarly, Ezeomedo and Ogbogu (2022) reported that only a fraction of oil palm wastes, such as POME, chaffs, palm kernel shells, and empty fruit bunches (EFBs), is utilized during production, with the rest discharged into the environment, further degrading soil quality. Ilyasu et al. (2024) stressed the importance of treating oil palm waste before releasing it into the environment, a sentiment echoed by Nwaugo et al. (2024), who noted that regulated quantities of POME can be beneficial for agriculture, while excessive amounts lead to environmental harm.

Conversely, the study observed that soil organic carbon (SOC) increased in the sampled soils compared to the control soils, likely due to POME's effect in enhancing SOC depending on the quantity applied. Soil physical conditions, such as particle size composition (sand, silt, and clay), WHC, and bulk density, also increased in the sampled soils relative to the control site. However, WHO does not specify permissible limits for these soil parameters. These findings align with Ogunbode et al. (2022), who similarly reported an increase in SOC and improvements in soil physical conditions in POME-affected soils compared to control soils.

IV. Conclusion And Recommendations

This study inquired about the soil pollution caused by the unregulated production of palm oil in Akwa-Ibom State. The study used the experimental design, and soil samples were analysed in the laboratory. The study's findings revealed notable differences in soil quality between the oil palm production sites and the control site. The content values of various parameters were higher than those recommended by the World Health Organization (WHO), which is attributed to the unregulated introduction of palm oil mill effluents (POME). Soil is a vital resource for supporting plant growth and development, and its degradation due to poorly managed oil palm production activities poses a serious concern. The study found that the key soil quality parameters—including pH, cation exchange capacity (CEC), nitrogen (N), phosphorus (P), potassium (K), and heavy metals—showed significant differences from WHO standards. Parameters such as water holding capacity (WHC), bulk density (BD), soil organic carbon (SOC), and heavy metals like Pb, Cr, and Ni were particularly affected in the oil palm production sites.

The study observed that soil organic carbon (SOC) increased in the sampled soils compared to the control soils, likely due to POME's effect in enhancing SOC depending on the quantity applied. Soil physical conditions, such as particle size composition (sand, silt, and clay), WHC, and bulk density, also increased in the sampled soils relative to the control site. However, WHO does not specify permissible limits for these soil parameters.

Following from these findings above, the following recommendations are advanced:

The oil palm producers should be charged with the responsibilities of producing palm oils sustainably. This can be achieved by the government providing certified bodies charged specially to ensure such compliance. Additionally, cleaner technological processes can be introduced by the government, for processing oil palm. Finally, the government should partner with the factory owners to management oil palm waste in the area more efficiently to avoid soil pollution.

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