DOI: https://doi.org/10.59983/s2025030403
AgroEnvironmental Sustainability, 2025, 3(4), 328–343

RESEARCH

Soil Physicochemical, Biochemical and Microbial Properties at Varying Proximities to Ten-Year-Old Palm Oil-Mill Effluent Dumpsite in Derived Savannah

Daniel Onyedikachi Ugwu[1,2], Prisca Oluchi Ogumba[3,4], Ndeari King Dedan[4,5], Parker Elijah Joshua[2], Sunday Ewele Obalum[4*], and Obioma Uzoma Njoku[2]

1 Department of Medical Biochemistry, Faculty of Basic Medical Sciences, David Umahi Federal University of Health Sciences, Uburu 491105, Ebonyi State, Nigeria
2 Department of Biochemistry, Faculty of Biological Sciences, University of Nigeria, Nsukka 410001, Enugu State, Nigeria
3 Department of Soil Science and Land Resources Management, College of Crop and Soil Sciences, Michael Okpara University of Agriculture, Umudike, PMB 7267 Umuahia, Abia State, Nigeria
4 Department of Soil Science, Faculty of Agriculture, University of Nigeria, Nsukka, 410001, Enugu State, Nigeria
5 Department of Soil Science, Faculty of Agriculture, Federal University of Kashere, PMB 0182 Gombe, Gombe State, Nigeria

* Corresponding author: Email: sunday.obalum@unn.edu.ng

ARTICLE HISTORY

Received: 12 August 2025
Revised: 28 September 2025
Accepted: 24 October 2025
Published: 15 December 2025

KEYWORDS

organic effluents
environmental degradation
enzyme activities
soil basal respiration
wastewater management
ecosystem quality
ecological wellbeing

eISSN 2583-942X

Abstract

This study assessed the physico-chemical properties, enzyme activities, and basal respiration of a sandy-loam soil around a ten-year-old palm oil mill effluent (POME) dumpsite at Inyi, a representative palm oil-processing community, in southeastern Nigeria. Sampling was from the POME dumpsite and at 20, 60, 100 and 260 m away. Soil pH ranged from alkaline (7.47) at the dumpsite to moderately acidic (5.83) 260 m away. Organic carbon, total nitrogen, and available phosphorus were highest (3.18%, 0.406%, and 76.79 mg/kg, respectively) in POME-dumpsite soil and decreased with distance away from it. The POME-dumpsite soil showed higher contents of the exchangeable bases (K^+, Ca^{2+}, Mg^{2+} and Na^+; 0.19, 9.33, 9.00 and 0.16 cmol/kg, respectively), cation exchange capacity (22.13 cmol/kg), base saturation (84.40%) and, hence, higher structure stability than the adjacent soils. Enzyme assays showed decreases in soil dehydrogenase activity with distance away from the dumpsite. Catalase activity was inhibited at the farthest point (260 m) away from the dumpsite, whereas lipase activity was nominally higher in the dumpsite (81.95 μgPNP/gmin) than in the adjacent soils. Basal respiration decreased only at 20 m away from the dumpsite. These results indicate improved soil fertility/health around POME dumpsites relative to directly unaffected surroundings. By positively influencing soil physico-chemical properties and enzyme/microbial activities, long-term controlled dumping of POME could enhance environmental quality. Understanding the interplay between these ecological benefits of controlled POME dumping and the widely acknowledged eco-toxic effects of POME is essential for developing its sustainable management strategies in palm oil-processing regions.

Citation: Ugwu, D. O. *et al.* (2025). Soil Physicochemical, Biochemical and Microbial Properties at Varying Proximities to Ten-Year-Old Palm Oil-Mill Effluent Dumpsite in Derived Savannah. *AgroEnvironmental Sustainability*, 3(4), 328–343. https://doi.org/10.59983/s2025030403

Statement of Sustainability: The processing of oil palm fruits into palm oil and other products is a thriving business in the tropics. Land dumping of the ensuing large volumes of palm oil-mill effluent (POME) as a means of its disposal – a practice which is often inevitable – has been viewed through the negative lens. This study found open dumping of POME to lead to enhanced soil fertility/health in the derived savannah agroecological zone of the humid tropics. The practice thus can have some ecological benefits which may compensate for the widely recognized toxic influence of this agro-waste in our tropical agro-ecosystems. This research contributes to Sustainable Development Goals (SDG), including SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

DOI: https://doi.org/10.59983/s2025030403
AgroEnvironmental Sustainability, 2025, 3(4), 328–343

1. Introduction

Palm oil production is an important agricultural cum economic activity in many tropical regions, including Nigeria where it contributes to the diet of many people (Bassey, 2016). It accounts for around 70% of the supply of domestic vegetable oil, as palm oil is reputed as one of the most widely used cooking oils in West African and neighbouring tropical countries (Nzeka, 2014; Boateng et al., 2016). About 80% of palm oil production comes from small-scale farmers who harvest semi-wild palm fruits and process them manually (Gunn, 2014). In Nigeria, most manual and mechanized processing mills are concentrated in the south-eastern region, where oil palm trees are endemic and grow both in the wild and on plantations (Ohimain et al., 2014; Okolo et al., 2019).

Nevertheless, the palm oil production industry is faced with challenges associated with the management and disposal of its by-products, notably, palm oil-mill effluent (POME). These effluents, rich in organic and inorganic compounds, are often discharged directly onto land without adequate treatment, raising serious concerns about their long-term environmental impact. Such a practice poses environmental risks if not properly managed, as untreated oil-mill effluents can release large quantities of greenhouse gases, pollute water systems, harm aquatic organisms (Hosseini and Abdul, 2015), and can be phytotoxic (Okorie et al., 2017; Ugwu et al., 2024). Untreated oil-mill effluents also hinder the activity of soil enzymes, and have a reductive effect on soil microbial activity (Ugwu et al., 2025).

In derived savannah agro-ecologies, the soil plays a vital role in sustaining agriculture and maintaining ecological balance. The discharge of untreated POME into the environment, especially over extended periods, may result in profound alterations to the soil's physical and biochemical properties, affecting its fertility, microbial activity, and overall health. The POME contains appreciable quantities of phenols/polyphenols, especially when fresh (Komilis et al., 2005), a high concentration of organic matter, with a biological oxygen demand ranging from 25,000 to 65,714 mg/L and a chemical oxygen demand ranging from 44,300 to 102,696 mg/L (Hashiguchi et al., 2021). It consists of 4-5% solids (mostly organic), 0.5-1% residual oil, around 95% water, and a high level of organic nitrogen (Onyia et al., 2001; Taye and Yifru, 2010). It is estimated that producing one tonne of crude palm oil annually generates 5-7.5 tonnes of water in the form of POME (Ahmad et al., 2003). Consequently, POME presents a significant challenge in oil palm factories because of its large volume and difficulties in disposal (Mohammad et al., 2021; Nwoko et al., 2010).

A common practice among local oil mills in Nigeria is the discharge of POME onto adjacent fields or into nearby pits, where it undergoes natural fermentation facilitated by indigenous microorganisms (Nwoko et al., 2012). While this traditional disposal practice may appear convenient, it carries significant environmental consequences. The direct release of oily liquids onto the land can lead to soil compaction and waterlogging (Umoren et al., 2019), inhibiting plant growth and causing vegetation die-off, while constituting air pollution. When it enters water bodies, POME transforms river conditions, often turning the water brown, thick, and odorous which result in pronounced aquatic pollution (Mohammad et al., 2021). Therefore, poorly managed disposal methods not only degrade terrestrial environments but also pose substantial risks to aquatic ecosystems, where contamination has been linked to adverse effects on fish populations and other aquatic life (Zulfahmi et al., 2021; 2023).

The unchecked land disposal of large volumes of untreated POME in the humid tropics has emerged as an environmental concern with adverse implications. Continuous indulging in this practice has been linked to alterations in soil characteristics, including its structure, fertility, and overall quality (Nta et al., 2020). Such changes in soil physicochemical properties can also disrupt the balance and functionality of microbial communities and enzyme activity, which define the health of soil ecosystems (Zhong et al., 2015). The toxic effects of fresh POME in the soil have received undue research attention in and beyond the humid tropics (Hashiguchi et al., 2021; Ogunbode et al., 2022), even when POME pollution or deliberated addition to soil generally can enhance physicochemical, biochemical, and microbiological properties of humid tropical soils (Eno et al., 2017; Ugwu et al. 2025). Information on how POME dumping influences these soil properties would help devise strategies for managing this effluent and mitigating the toxicity of its fresh form on the agro-environment (Wang et al., 2023), translating into its proper management to the benefit of sustainable agricultural development of tropical Africa (Baiyeri et al., 2020).

In this study, we assessed the soil physicochemical properties as markers of soil quality and fertility alongside enzymatic/microbial activities as markers of soil health, at varying proximities to a ten-year-old POME dumpsite at Inyi in the derived savannah of southeastern Nigeria. The objective was to expose any spatial trends in soil physical properties (particle size fractions), physicochemical properties (soil pH, organic carbon, and primary nutrients), and soil structure deformation from the dumpsite outwards. By also examining the spatial trends in the activities of soil

DOI: https://doi.org/10.59983/s2025030403
AgroEnvironmental Sustainability, 2025, 3(4), 328–343

enzymes (dehydrogenase, catalase, and lipase) and microbes, we gained insight into the influence of the practice of POME dumping on metabolic functions and microbial communities. With information on such trends for these soil quality/health attributes, we contribute to the broader discourse on sustainability and environmental stewardship concepts in the palm oil industry of the agricultural sector of tropical countries. The overall aim was to add to the understanding of the impact of this age-long practice on environmental quality.

2. Materials and Methods

2.1. Description of the Study Area

The study was carried out at Inyi in Orji River Local Government Area of Enugu State of Nigeria. Inyi shares boundaries with Achi, Ugwuoba, Akpugoeze, and Ufuma, and is about 60 km to Enugu, 45 km to Awka, and 35 km to Nnewi, all in Enugu and Anambra States in the South-East, Nigeria. There are nine villages in Inyi with Umuome and Enugu-Inyi at the heart of the town. Mean annual rainfall is in the range of 1.5-2.0 m, while mean minimum and maximum temperatures are 18 and 36°C, respectively. The soil in Inyi is predominantly sandy loam and the vegetation is typical of derived savannah. The majority of the town's active population are peasant farmers and businessmen. The processing of oil palm fruits into palm oil and sale of the latter is a thriving business in the town.

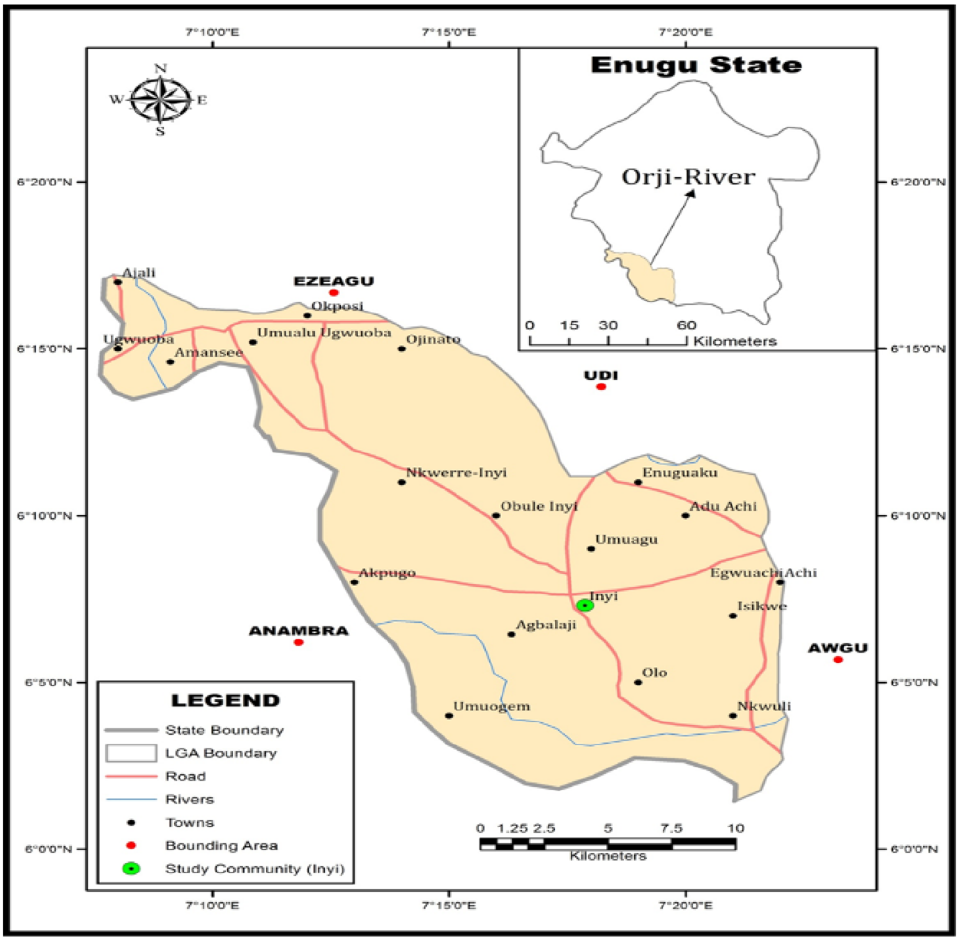

Figure 1a. Map of Enugu State in the South-East, Nigeria showing Orji River Local Government Area and Inyi as one of its communities with the different soil sampling sites within the community.

2.2. Collection of Soil Samples

Soil samples were collected at and adjacent to a POME dumpsite (open pit), situated at Inyi in Oji River Local Government Area of Enugu State in the South-East, Nigeria (**Figures 1a** and **1b**). The terrain represented a gentle slope of ca. 5% falling from the dumpsite outwards, ensuring lateral drainage in this direction and not otherwise. The dumpsite was over 10 years old as at the time of this study, and soil sampling took place during the rainy season (April – October). A sampling transect was established, and samples collected this transect and and in the direction of the slope at pre-determined intervals (Joseph et al., 2025). Soil samples were collected from the periphery of the POME dumpsite and at 20, 60, 100 and 260 m away from it (**Table 1**). Topsoils (0–15 cm) were collected in quadruplicates using a soil auger and placed into polythene bags. A walker meter was used to measure the distance away from the POME dumpsite, along the sampling transect on ca. 5% slope. The soil samples were taken to the laboratory where they were air-dried to constant weight, gently crushed, and sifted through a 2-mm sieve to collect the fine-earth particles for analyses.

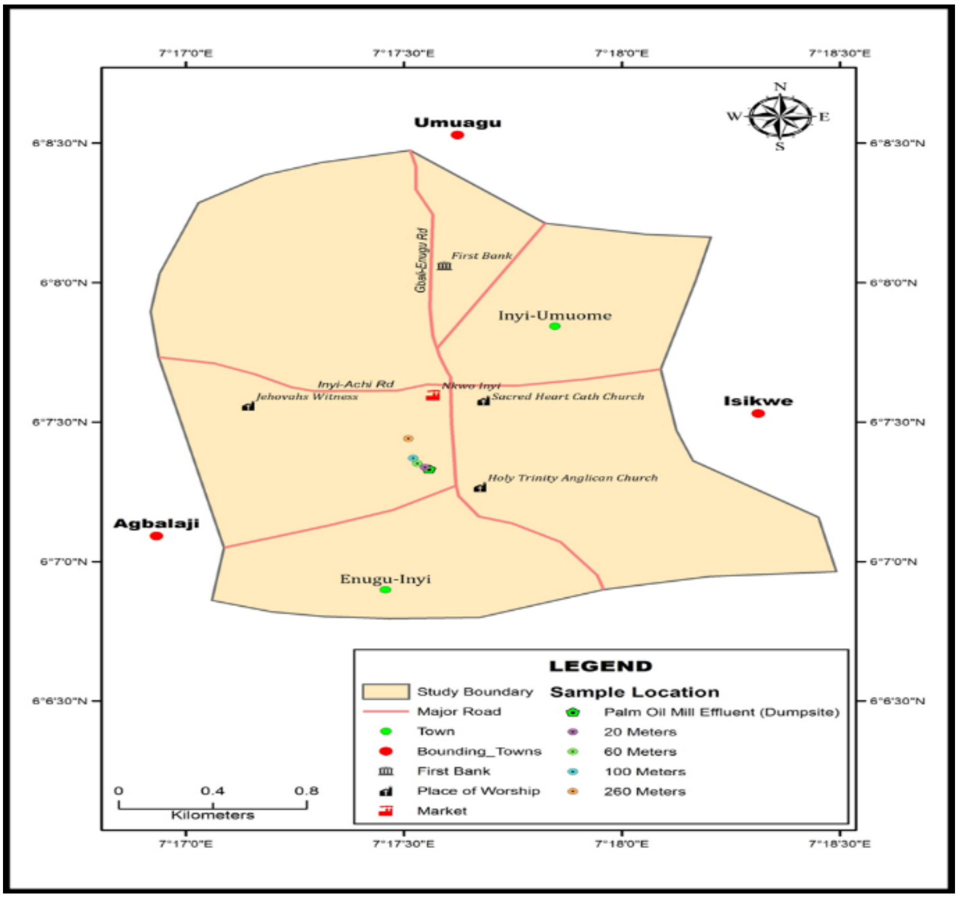

Figure 1b. Map of Enugu State in the South-East, Nigeria showing Orji River Local Government Area and Inyi as one of its communities with the different soil sampling sites within the community.

Table 1. Sampling sites at and some distances away from the palm oil-mill effluent (POME) dumpsite and their geo-coordinates at Inyi in the derived savannah of south-eastern Nigeria.

Sampling site	GPS location
POME dumpsite	N 06° 07.332, E 007° 17.557
20 m from POME dumpsite	N 06° 07.338, E 007° 17.548
60 m from POME dumpsite	N 06° 07.352, E 007° 17.534
100 m from POME dumpsite	N 06° 07.371, E 007° 17.521
260 m from POME dumpsite	N 06° 07.441, E 007° 17.510

2.3. Laboratory Soil Analyses

2.3.1. Analyses for Soil Physicochemical Properties

Soil pH was measured using deionized water and 0.1 N KCl suspensions in a 1:2.5 soil-to-liquid ratio (McLean, 1982) with a Beckman's zeromatic glass electrode pH meter. Soil organic carbon (SOC) content was determined by the Walkley–Black wet dichromate oxidation method (Nelson and Sommers, 1982). Total nitrogen was measured through micro-Kjeldahl digestion and distillation as described by Bremner and Mulvaney (1982). Available phosphorus was extracted with Bray 2 solution and quantified using a colorimetric method (Olsen and Sommers, 1982). The cation exchange properties of the amended soil were assessed as follows: soil samples were leached with 1 N NH_4OAc (pH 7), and the resulting exchangeable potassium and sodium (K^+ and Na^+, respectively) in the leachate were measured using a flame photometer. Exchangeable bases of calcium and magnesium (Ca^{2+} and Mg^{2+}, respectively) in the leachate were determined through complexometric titration (Thomas, 1982). Cation exchange capacity (CEC) was measured using the NH_4OAc displacement method (Rhoades, 1982). The percent base saturation was calculated by totaling the exchangeable bases (K^+, Ca^{2+}, Mg^{2+}, and Na^+), dividing this total by the CEC, and then multiplying the result by 100. Soil exchangeable acidity (exchangeable aluminium and hydrogen) was measured using the method outlined by McLean (1982). Soil mechanical analysis was done using the hydrometer method, and particle size distribution was measured following the procedure described by Gee and Bauder (1986). Each parameter was analyzed in triplicate. Structure stability index (SSI) of the soils, an indicator of the risk of soil structure deformation due to SOC depletion (Obalum et al., 2012, 2013a, b; Jidere et al., 2025), was also calculated as follows:

$$SSI = \left(\frac{1.724 \ \times \ \%SOC}{\%Silt \ + \ \%Clay} \right) \times 100 \qquad (1)$$

2.3.2. Determination of Soil Biochemical Properties

Dehydrogenase activity of the soil was assayed following the procedure outlined by Tabatabai (1982). In the procedure, 1 g of soil was mixed with 1 ml of 3% aqueous 2,3,5-triphenyl tetrazolium chloride in a test tube, incubated for 96 hours at 27°C, and then mixed with ethanol. After vortexing the mixture and allowing the suspended soil particles to settle, the supernatant was measured spectrophotometrically at 485 nm. The concentration of formazan formed during the decomposition of 2,3,5-triphenyl tetrazolium chloride by dehydrogenases was calculated using an extinction coefficient of 15,433 mol cm^{-1} (Dushoff et al., 1965).

Soil catalase activity was assayed following the procedure outlined by Cohen et al. (1970). This method involved mixing 10 g of soil with 100 ml of phosphate buffer at pH 7.4 and filtering the suspension through a cheese cloth. The resulting filtrate was centrifuged to obtain the supernatant. Catalase activity was assessed by quantifying the breakdown of hydrogen peroxide using an excess of potassium permanganate ($KMnO_4$). The mixture of supernatant and hydrogen peroxide was reacted, and the remaining $KMnO_4$ was measured spectrophotometrically at 480 nm. A spectrophotometer standard was prepared as a combination of $KMnO_4$, phosphate buffer, and sulfuric acid, and the spectrophotometer was calibrated with distilled water before readings were taken.

The assay for soil lipase activity followed Margesin et al.'s (2002) method. In the procedure, 0.1 g of soil was mixed with a NaH_2PO_4/NaOH buffer (pH 7.25) and pre-warmed at 30°C. After adding a substrate solution of p-nitrophenyl butyrate (pNPB), the mixture was kept at 30°C for 10 minutes to incubate to allow the reaction to occur. The reaction was stopped by placing the tubes on ice for 10 minutes. The contents were centrifuged, and the supernatant collected to measure the release of p-nitrophenol (pNP) spectrophotometrically at 400 nm. A control without soil was used for comparison. Calibration curves with different concentrations of pNP were prepared for reference. After accounting for the control, soil lipase activity was measured as the quantity of pNP produced per gram of dry soil within 10 minutes.

2.3.3. Determination of Soil Basal Respiration

Basal respiration was determined by adapting the method of Isermeyer (1952). It involved adjusting 50 g of soil to 60% water holding capacity in a plastic tube and placing the plastic tube and its content in the bottom of a Duran bottle. Then 25 ml 0.05N NaOH was pipetted and suspended on the soil sample (to trap evolved CO_2) and incubated for 7 days. After incubation, the bottle was opened and beakers containing NaOH solution were emptied into the jar containing 5 ml 0.5M barium chloride solution and some drops of the indicator were added in the solution and titrated with 0.05M HCl under continuous stirring until the color changes from red to colorless. The NaOH without soil was used as a control. The rate of microbial respiration was calculated using the formula (Eze et al., 2018):

$$CO_2(mg)/sw/t = (V0 - V) \times \frac{1.1}{dwt} \quad (2)$$

where sw is dry weight of soil (g), t is incubation time (h), V_0 is average titre value of blank, V is titre value of sample, dwt is dry weight of 1 g of soil, and 1.1 is the conversion factor.

2.4. Statistical Analysis

Statistical Package for Social Sciences (SPSS) version 18.0 was employed for data analysis. Data were examined for differences among the five sampling points (the POME dumpsite and distances away from it) using a one-way analysis of variance, and mean values with different superscript letters were deemed significant ($p < 0.05$).

3. Results

3.1. Particle Size Distribution of Soil at and Distances away from the POME Dumpsite

The results of the particle size distribution of soil samples collected from a POME dumpsite and some distances away from the POME dumpsite are shown in **Table 2.** Soils collected from the POME dumpsite and at 20, 60, 100 and 260 m away from it were all classified as sandy-loam soils, with generally smaller percentages of fine sand than coarse sand. The dumpsite soil had the highest coarse sand content of 52%, the lowest fine sand content of 33%, and relatively low clay and silt contents. However, the soil sample taken 260 m away from the dumpsite recorded the highest clay (11.67%) and silt (13.33%) contents and the lowest coarse sand content (37.33%).

Table 2. Particle size distribution of soil samples collected from the palm oil-mill effluent (POME) dumpsite and some distances away from the dumpsite.

Soil Sample	% Particle Size Distribution				Texture Class
	Clay	Silt	Fine Sand	Coarse Sand	
POME dumpsite	8.33 ± 0.58^a	7.00 ± 0.00^a	33.00 ± 0.00^a	52.00 ± 0.00^d	Sandy loam
20 m away from dumpsite	8.00 ± 0.00^a	6.67 ± 0.58^a	37.00 ± 1.00^c	48.33 ± 1.15^c	Sandy loam
60 m away from dumpsite	7.67 ± 0.58^a	7.33 ± 0.58^a	35.33 ± 1.15^b	49.67 ± 1.15^c	Sandy loam
100 m away from dumpsite	8.00 ± 0.00^a	9.00 ± 0.00^b	39.00 ± 0.00^d	44.00 ± 0.00^b	Sandy loam
260 m away from dumpsite	11.67 ± 0.58^b	13.33 ± 0.58^c	38.00 ± 0.00^{cd}	37.33 ± 0.58^a	Sandy loam

Values are means ± standard deviations (n = 3), and means for each particle size fraction on a column bearing different letters as superscripts differ significantly ($p < 0.05$).

3.2. Soil Physicochemical Properties at and Distances away from the POME Dumpsite

Figure 2a shows that the soil pH ranged from 7.47 (alkaline) in the POME dumpsite to 5.83 (moderately acidic) at the farthest distance - 260 m away. The SOC content (3.18%) and total nitrogen (0.406%) were highest at the dumpsite, decreased with distance away from it, but showed the second highest values at the farthest distance (**Figure 2b**). Nevertheless, soil from the POME dumpsite recorded the highest available phosphorus content (76.79 mg/kg) and decreased ($p < 0.05$) with increasing distances away from the POME dumpsite (**Figure 2c**). **Figure 3a** shows significant ($p < 0.05$) changes in the concentrations of exchangeable potassium (K^+) and sodium (Na^+) across soil samples taken from a POME dumpsite and farther distances from it. The soil sample from the POME dumpsite had the highest concentrations of both K^+ (0.19 cmol/kg) and Na^+ (0.16 cmol/kg), which is consistent with the chemical composition of POMEs known to be rich in dissolved elements including potassium and sodium (Ugwu et al., 2025). At 20 m and 60 m away from the dumpsite, there was a marked decline in the concentrations of both exchangeable K^+ and Na^+, with values dropping to 0.11 and 0.08 cmol/kg at 20 m, and 0.10 and 0.06 cmol/kg at 60 m, respectively.

Figure 3b shows that Ca^{2+} and Mg^{2+} contents of the soil samples collected from the POME dumpsite were significantly different from those of the soils collected distances away from the dumpsite. The results showed that the highest values were observed in soil collected from the dumpsite, with Ca^{2+} at 9.33 cmol/kg and Mg^{2+} at 9 cmol/kg. As the distance from the dumpsite increased, there was a notable decline in both Ca^{2+} and Mg^{2+} concentrations. At 60 m, Ca^{2+} dropped to 4.73 cmol/kg, while Mg^{2+} dropped to 1.8 cmol/kg, representing the lowest for both cations in the study. The exchangeable H^{+} concentrations across the soil samples show that the soil acidity and chemical buffering varied in relation to proximity to the POME dumpsite (**Figure 3c**). The highest H^{+} was observed at the POME dumpsite (1.8 cmol/kg), while its lowest concentration was at 60 m away from the dumpsite (1.27 cmol/kg).

3.3. Soil Apparent CEC and Base Saturation at and Distances away from the Dumpsite

Figure 3d presents the apparent cation exchange capacity (CEC) of the soil – its ability to retain and exchange essential plant nutrients – at varying distances to the POME dumpsite. The highest apparent CEC was observed at the dumpsite (22.13 cmol/kg), indicating a high soil nutrient-holding and exchange capacity. However, the lowest apparent CEC was recorded at 100 m (7.53 cmol/kg), closely followed by 60 m (7.73 cmol/kg) away from the dumpsite.

Figure 3e shows that the base saturation, the proportion of soil exchange sites occupied by base-forming cations, varied across different proximities to the POME dumpsite. The highest base saturation was recorded at 20 m away from the dumpsite (93.84%), beyond which the values decreased progressively with distance until the farthest 260 m (74.42%). However, the POME dumpsite with a value of 84.40% differed only from this farthest distance.

3.4. Soil Structure Stability at and Distances away from the POME Dumpsite

The results for the structure stability index (SSI) of the soil at the POME dumpsite and some distances away from it are shown in **Figure 4**. This index represents the ratio of soil organic matter to the sum of clay and silt particles, and reflects how soil aggregates withstand external physical forces, such as compaction and agents of erosion. This SSI indicated higher values at the POME dumpsite (35.68%) than at all the other four sampling points at varying distances away from the dumpsite, for which values were similar (14.67% to 18.61%).

3.5 Soil Enzyme Activities at and Distances away from the POME Dumpsite

Dehydrogenase activity reflects the microbial oxidative metabolism in soil, serving as a strong indicator of biological functioning and soil health. Figure 5a shows that the POME dumpsite had the highest dehydrogenase activity at 2.95 μg/g, which was significantly greater than all other samples. The lowest occurred at 260 m away from the dumpsite (0.97 μg/g). **Figure 5b** shows that the highest catalase activity was recorded at 20 m away from the POME dumpsite (17.39 k/min), while the lowest was observed at 260 m (15.06 k/min). At the dumpsite, the catalase activity (16.13 k/min) was slightly lower than at 20 m.

Lipase activity, reflects the soil's enzymatic ability to hydrolyze lipids, and is closely related to microbial function, organic substrate availability, and effluent impact. The highest lipase activity was observed at the POME dumpsite with a value of 81.95 μgPNP/gmin, while the lowest lipase activity was recorded at 60 m away from the dumpsite (63.12 μgPNP/gmin), slightly lower than the value at 260 m (65 μgPNP/gmin) (Figure 5c).

3.6. Soil Basal Respiration at and Distances away from the POME Dumpsite

Figure 5d shows the basal respiration rate of soils at the POME dumpsite and distances away from the dumpsite. The results showed that the highest basal respiration rates were observed at both 100 and 260 m away from the POME dumpsite, each recording 14.59 mg/g/h. The basal respiration was found lower at 20 m (12.48 mg/g/h) than the rest, including the dumpsite with a value of 13.91 mg/g/h, slightly lower than more distant spots.

4. Discussion

The higher coarse sand content of the POME dumpsite could imply that effluent deposition may have disrupted the soil structure, removing finer particles via water erosion and chemical degradation. The presence of organic acids and residues in POME interferes with particle cohesion and encourages leaching and aggregate breakdown, which favours the accumulation of coarser particles (Nasrin and Hassan, 2020). The generally low silt and clay contents of the soil imply poor moisture retention and nutrient availability, which is typical of physically degraded soils (Obalum and Obi, 2013; Adegbite and Olatunji, 2022). The improved soil texture quality 260 m away from the dumpsite indicates minimal influence of the effluent. The increased clay and silt contents of the soil at this farthest distance may lead to increased aggregation, water-holding capacity and soil fertility, due to stabilized organic content and restored microbial processes. Ogunbode et al. (2022) observed that as distance increased from the contamination source, finer particles remained intact due to reduced chemical stress and enhanced biological activity.

The alkaline soil pH at the dumpsite may be due to the liming effect of the naturally fermented, biodegraded POME inside the dumpsite (Anele et al., 2025a). Soil pH influences nutrient bioavailability, as H^+ occupies space on the negatively charged soil surface, thereby displacing nutrients. Indeed, soil pH influences the soil's overall capacity to retain and provide nutrients from its exchange sites (McCauley et al., 2017). Although the values of soil pH at and distances away from the POME dumpsite were within the range (5.5–7.5) for optimum microbial activity and plant growth (Landon, 1991), the shift toward acidity at distances away from the dumpsite could be an indicator of an overall decline in soil health as one moves away from pits for collecting POME in palm oil-processing areas.

The increased SOC at the POME dumpsite, compared to areas farther away, may be due to the breakdown of POME's organic and solid components by microorganisms (Maduwuba, 2024). Similar to this observation, Nwachukwu et al. (2018) reported increases in SOC content in POME-polluted topsoils over their non-polluted counterparts. High organic carbon in POME dumpsite soil could be attributed to the natural fermentation of the POME with aging which, over time, converts the POME into biofertilizer (Ugwu et al., 2024), as evident in the higher total nitrogen and available phosphorus at the dumpsite than at distances away from it (Anele et al., 2025a). Notably, soil total nitrogen and available phosphorus at the dumpsite exceeded the suggested ranges of 0.16-0.19% and 30-50 mg/kg, respectively for optimum crop production (Adhikari et al., 2018). Their high levels could lead to nutrient imbalance, leaching into underground water, and runoff into nearby water bodies (Pahalvi et al., 2021), causing eutrophication and degradation of aquatic ecosystems, and so have adverse impacts on both agriculture and the environment.

The elevated levels of soil contents of K^+ and Na^+ at the dumpsite reflect the sustained direct ionic loading of the dumpsite with carbon-rich POME (Ogunbode et al., 2022). Proximity to the effluent source ensures direct exposure to chemical inputs, enhancing the availability of these exchangeable bases through sustained contamination and accumulation (Anele et al., 2025a). The enrichment with K^+ and Na^+ thus reflects both the mineralization of carbon and composition of the effluent as repeatedly deposited over time.

The reductions in K^+ and Na^+ at distances away from the dumpsite indicate dilution and attenuation of effluent influence with increasing distance. Contrary to our data, Farahani (2025) observed reduced nutrient concentrations as a result of effluent-induced changes in soil structure and porosity near a dumpsite, leading to excessive downward leaching of soluble ions. The K^+, though more retained by soil particles than Na^+, still decreased with decreased input due possibly to greater mobility in soil solution and hence susceptibility to leaching as well as higher uptake by vegetation at these transitional distances.

The increases in levels of Ca^{2+} and Mg^{2+} at the POME dumpsite would be explained by the high concentrations of divalent cations in POME due to its organic and mineral constituents (Ugwu et al., 2025). The effluent enriches the soil through sustained accumulation of organic matter, thereby enhancing its CEC and boosting nutrient retention near the source (Izah and Ohimain, 2016). The reductions in Ca^{2+} and Mg^{2+} levels at distances away from the dumpsite were likely due to reduced deposition and leaching that dilute or redistribute nutrients (Anwar and Arshad, 2015). Additionally, biological uptake and water movement could further contribute to the decreased availability of these nutrients with distance. The relatively high values of Ca^{2+} compared to Mg^{2+} may be attributed to the greater susceptibility of the latter to leaching, as it is less strongly adsorbed onto soil particles (Evanylo, 2024).

Soil exchangeable H^+ showed the highest value at the dumpsite. This was most likely due to microbial decomposition of organic substrates in POME, releasing acidifying compounds (Sharifah et al., 2021). These authors noted that the accumulation of H^+ reflects enhanced acid saturation and points to potential soil acidity problems, especially under prolonged effluent exposure. Indeed, as soil H^+ increases, the more acidic the soil becomes (Obalum et al., 2012a; 2012b). This, however, was not the case in the present study, as soil pH was also highest at the dumpsite. The alkaline pH of POME which was due to its –OH group might have made other sources of acidity to have stronger influence than H^+ on soil pH of oil mill-affected tropical soils (Okorie et al., 2017; Ugwu et al., 2024).

The increase in soil apparent CEC at the dumpsite would be explained by the heavy accumulation and decomposi-

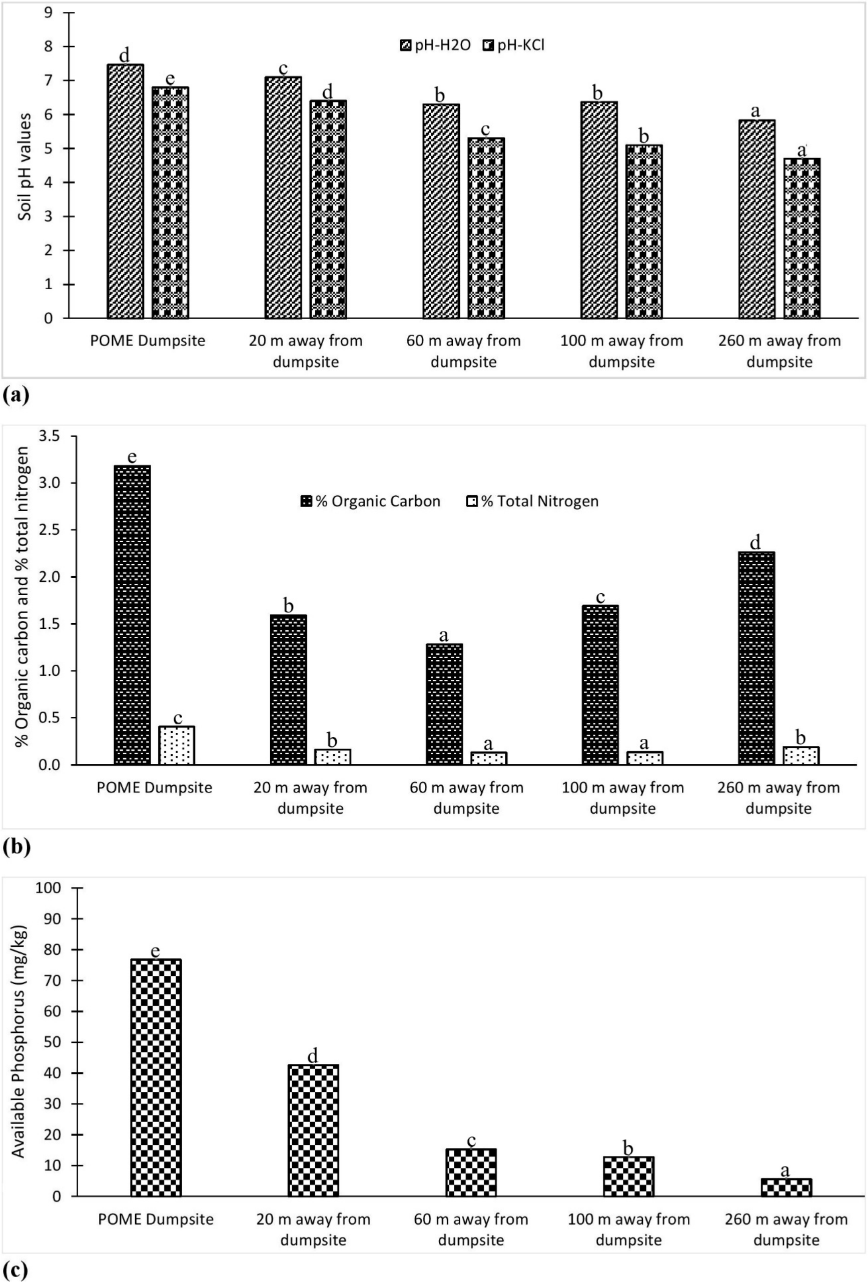

Figure 2. Soil pH (a), organic carbon and total nitrogen (b) and available phosphorus (c) of the soil at and some distances away from the ten-year-old POME dumpsite at the derived savannah of southeastern Nigeria. Means bearing different letters differ significantly ($p < 0.05$).

tion of POME with its residue, increasing organic matter which enhances the soil colloidal properties, thereby increasing surface charge (Martínez-Alvarez et al., 2018) and hence CEC (Obalum et al., 2013b). Effluent-saturated soils tend to exhibit higher microbial activity and greater concentrations of humic substances, both of which contribute to increasing reactive sites and CEC. The reduced CEC beyond the POME dumpsite could imply diminished influence of the effluent and a return toward natural soil conditions. Obalum et al. (2013b) and Maduwuba (2024) noted that sandy-loam soils of the savannah generally exhibit lower apparent CEC values due to their limited clay and organic matter contents. This may have contributed to the decreases in CEC at distances away from the POME dumpsite.

Base saturation indexes the soil fertility status as the dominance of base-forming cations such as K^+, Ca^{2+}, Mg^{2+} and Na^+ over acidic ones like H^+ (Zalewska et al., 2023). At the POME dumpsite, base saturation was moderately high, likely due to a direct influx of the nutrient-rich effluent. However, it did not surpass the peak value at 20 m, possibly

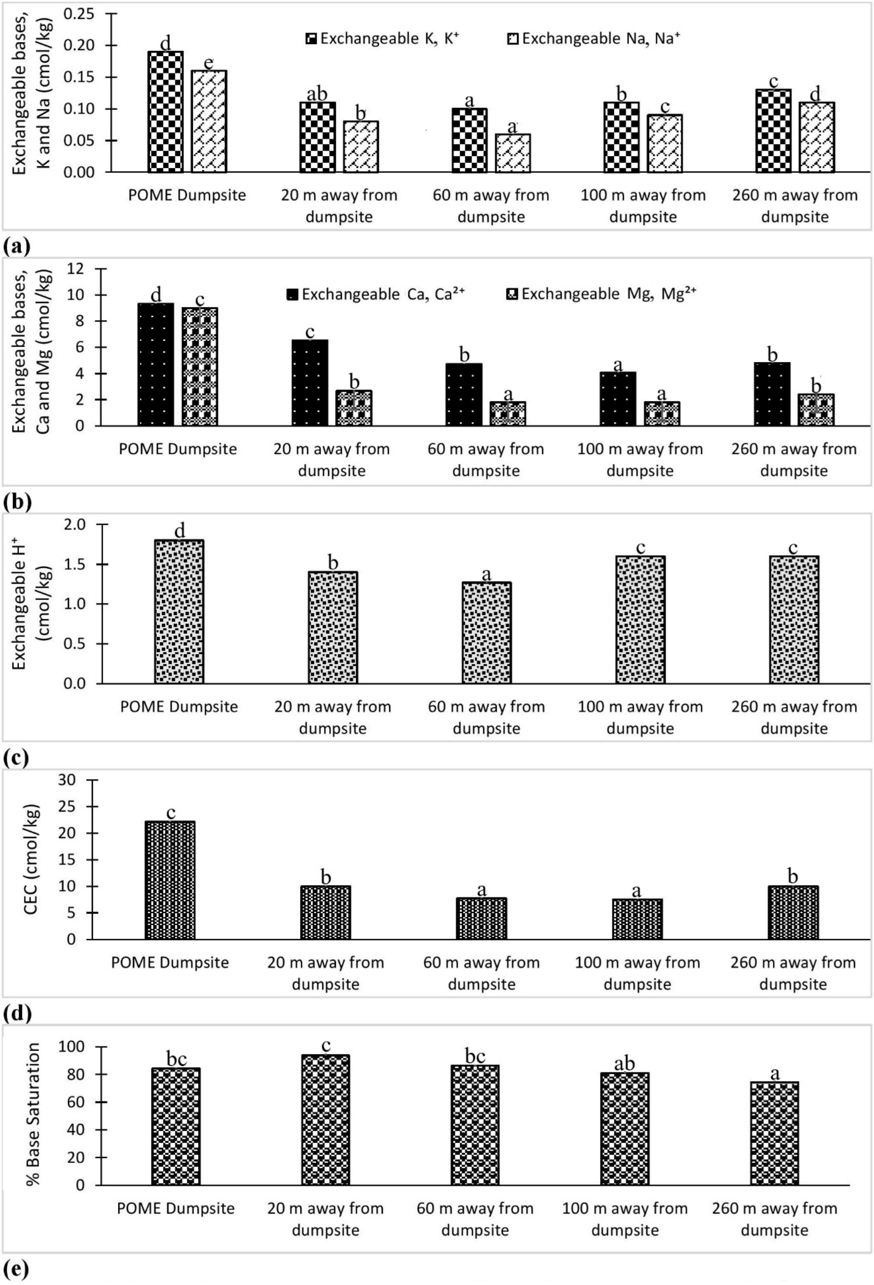

Figure 3. Cation exchange indices; contents of K+ and Na+ (a), contents of Ca2+ and Mg2+ (b), content of H+ (c), apparent CEC (d), and base saturation (e) of the soil at and some distances away from the from the ten-year old POME dumpsite at the derived savannah of south-eastern Nigeria (Means bearing different letters differ significantly (p < 0.05).

because excessive organic acids and ion competition from the effluent reduce the efficiency of retention of base-forming cations despite the presence of high nutrient levels (Zhao et al., 2016). The influence of POME 20 m away from the dumpsite was perhaps moderated to allow for maximum nutrient retention. This could be due to residual dispersion of effluent components, which enriches the soil without overwhelming its structure (Heinen, 2017). The neutral soil pH and reduced H^+ at this 20-m distance possibly increased organic decomposition, leading to greater retention of base-forming cations. The decrease in base saturation 260 m away from the dumpsite may be due to reduced nutrient inputs and increased H^+ occupying the exchange sites, implying increased soil acidity and decreased soil fertility (Xie et al., 2021), as well as a weaker soil buffering capacity.

Notably, oil-mill effluents, especially fresh ones, typically contain appreciable quantities of phenols and polyphenols

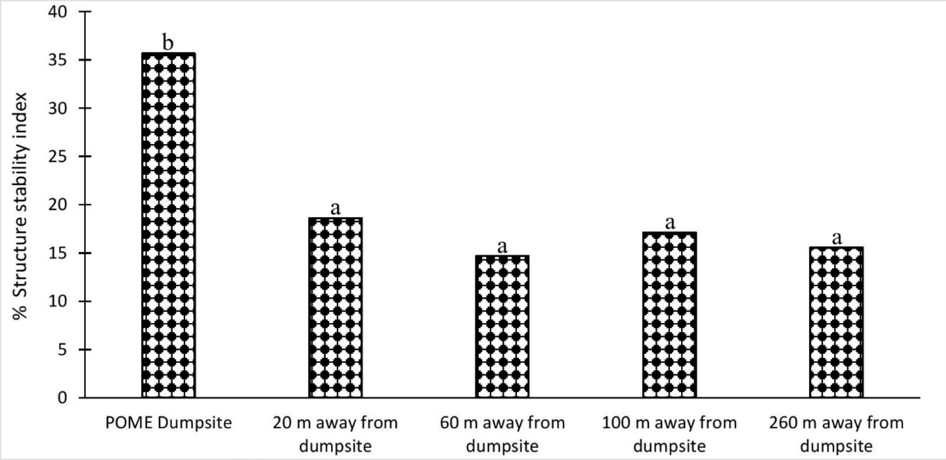

Figure 4. Structure stability index of the soil and at some distances away from the from the ten-year old POME dumpsite at the derived savannah of south-eastern Nigeria. Means bearing different letters differ significantly (p < 0.05).

(Komilis et al., 2005), and these compounds have been reported to be phytotoxic (Okorie et al., 2017). Also, POME's biological oxygen demand can be high and vary greatly, depending on its organic load (Hashiguchi et al., 2021; Ugwu et al., 2024). Because of these concerns, the POME-induced increases in soil fertility here should be taken with caution, for such POME-affected soils may pose both environmental pollution and eco-toxic risks.

The increase in soil structure stability at the dumpsite was primarily due to the continuous influx of organic compounds and microbial stimulation resulting from effluent exposure (Anele et al., 2025b). Organic matter, especially humic substances, acting as a binding agent, promotes soil aggregation (Obalum et al., 2017). This is primarily through complexation with fine particles to form granular 'porous' aggregates, a situation that renders the soil infiltrable (Oguike et al., 2023; Enemo et al., 2025), implying reduced runoff and erosion. Byproducts of POME, including polysaccharides, enhance aggregate cohesion, allowing the soil to resist mechanical rupture and erosion (Omoregie et al., 2024). Conversely, beyond the dumpsite, there was a reduction in organic input and microbial activity. The associated decreases in soil-binding substances and microbe-driven aggregation may have led to dominance of weak and unstable soil aggregates (Iqbal et al., 2025). This would explain the observed decreases in soil structure stability between 20 and 260 m away from the dumpsite. Within this zone, however, the SSI for the soil was 'high', going by rating of Mukherjee and Lal (2014) and Pulido-Moncad et al. (2015), where values < 5%, 5%–7%, and > 9% indicate soils that are structurally degraded, at high risk of degradation, and with sufficient carbon, respectively.

Dehydrogenase, being an intracellular enzyme involved in energy production, becomes active as microbes metabolize available substrates. The reduced dehydrogenase activity at 260 m away from the POME dumpsite indicates a minimal microbial oxidative response, signaling soil microbial system operating at a much lower intensity. Microbial biomass here is likely low, and respiration-driven enzyme production is minimal, reflecting the natural background levels of soil microbial activity in the absence of effluent-induced stimulation. Therefore, reduced organic input leading to nutrient-poor soil and few bioavailable nutrients would explain the reduced soil dehydrogenase activity at 260 m away from the POME dumpsite (Kumar et al., 2013; Ogumba et al., 2020).

Catalase activity at the dumpsite was slightly lower than at 20 m, possibly due to inhibitory effects of high organic load or the presence of toxic compounds in freshly added POME. Although the effluent introduces abundant organic material, excess nutrients and anaerobic conditions might suppress certain microbial functions, resulting in sub-optimal catalase expression. The increase in catalase activity at 20 m suggests that this is a zone where soil microbes thrive, due to moderate enrichment from organic residues in the POME (Dvořáčková et al., 2022). At this distance, optimal conditions for microbial proliferation and enzymatic activity existed, and the nutrients in the effluent stimulated microbial metabolism without toxifying the system. On the other hand, the lowest catalase activity at 260 m away from the POME dumpsite signifies declining soil microbial activity and reduced availability of organic substrates, likely due to reduced external inputs and a more natural equilibrium (Liu et al., 2008).

The highest lipase activity at the dumpsite highlights the organic load of POME, which is rich in carbon, fatty acids

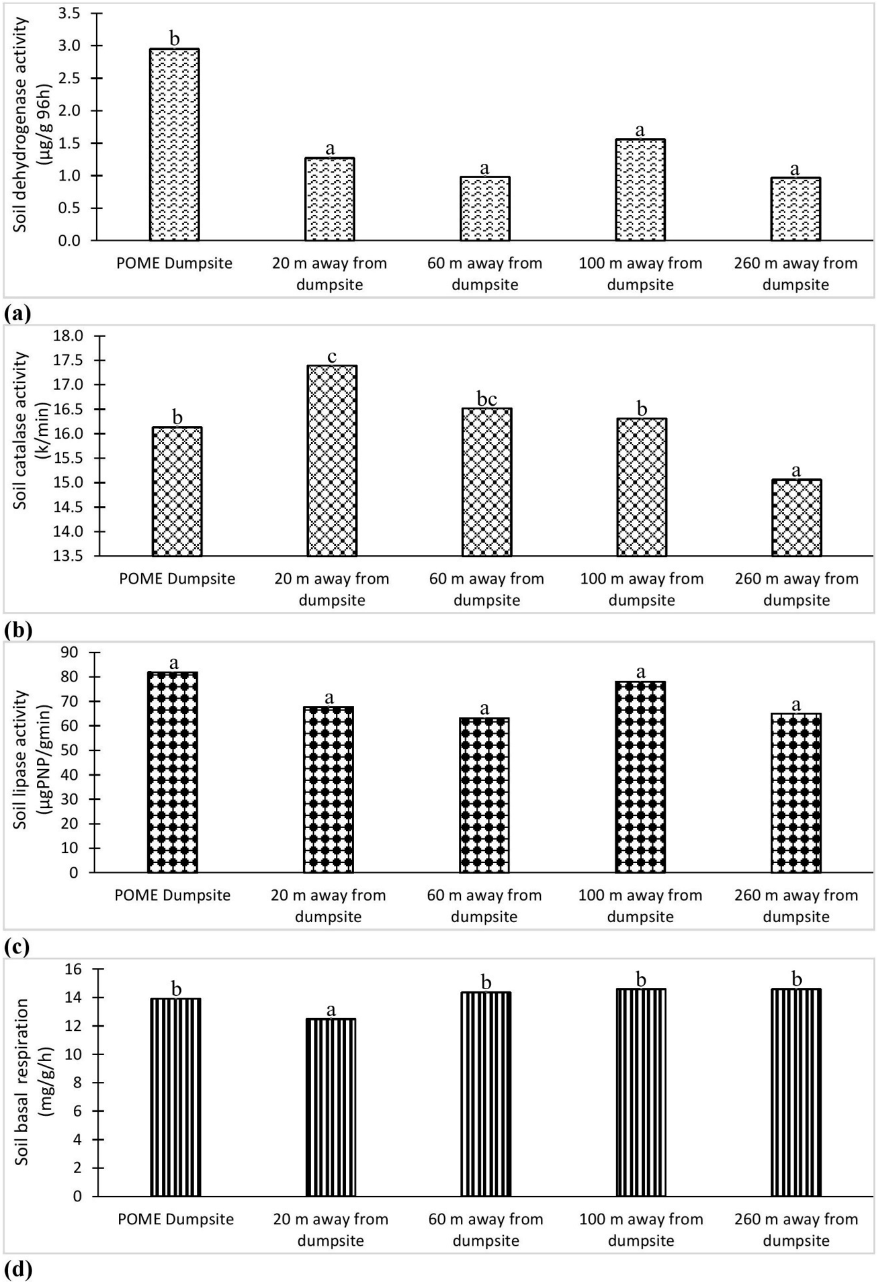

Figure 5. Activity of soil enzymes including dehydrogenase (a), catalase (b) and lipase (c) alongside soil basal respiration (d) at and some distances away from the ten-year-old POME dumpsite at the derived savannah of southeastern Nigeria. Means bearing different letters differ significantly (p < 0.05).

and lipid-based compounds. The presence of such organic materials stimulates lipase-producing microbes, resulting in heightened enzymatic activity as they metabolize these compounds for energy and growth (Nwachukwu et al., 2018), hence the observed highest lipase activity at the POME dumpsite (Ugwu et al., 2025). The POME is thus a source of many nutrients which catalyze microbial growth and cellular respiration.

The increases in basal respiration at 100 m and 260 m away from the POME dumpsite indicate that soil microbial communities at these sites are active and possibly functioning in more balanced, less chemically stressed environments. Despite being farther from the POME source, these two sites may have harboured richer soil microbial biodiversity and more stable carbon pools from native organic matter compared to what prevailed due to POME contamination. The increased basal respiration could also result from microbial adaptation or effective decomposition of naturally occurring substrates in soils that have regained their equilibrium (Nwaogu et al., 2012).

In contrast, the reduction in basal respiration rate at 20 m away, though still relatively high, points to the transitional microbial dynamics. The soil organisms might be at the phase of adjusting from the stress of residual effluent or variable substrate quality. It could also be that microbial metabolism was inefficient, possibly constrained by localized chemical imbalances or low oxygen diffusion resulting from POME-related soil compaction (Nwuche et al., 2013). The POME dumpsite showed a basal respiration that was slightly lower than the values at distances away from the dumpsite. One might expect the reverse to be the case due to the high organic load of the effluent. However, excessive concentrations of fatty acids, phenolic compounds, and other pollutants in especially freshly added POME could inhibit microbial efficiency or favour specialized populations that do not exhibit high basal respiration rates. This environment may induce anaerobic conditions or microbial stress that lowers overall aerobic metabolic output.

5. Conclusion

The study shows that long-term palm oil mill effluent (POME) dumping influences soil physico-chemical properties, and enzyme and microbial activities in tropical agro-ecologies. Despite the alkaline soil pH and higher organic matter content of the POME dumpsite, soil catalase activity remained unaffected, indicating microbial resilience. While soil dehydrogenase activity increased, lipase activity showed no change, suggesting potential inhibitory factors. High levels of cations exchange in the POME-affected soil indicate increased soil fertility, but also raise concerns about nutrient imbalances and their negative agronomic and environmental implications. This, coupled with the widely recognized environmental pollution and eco-toxic effects of POME, calls for caution in associating controlled POME dumping with increases in soil fertility. Understanding the physicochemical, biochemical, and microbial changes in POME-affected soils and their eco-agronomic implications is thus crucial for devising effective management practices toward environmental stewardship while increasing soil productivity in palm oil-processing tropical regions.

Authors' Contributions

Conceptualization: Daniel Onyedikachi Ugwu, Obioma Uzoma Njoku; Data curation: Ndeari King Dedan, Parker Elijah Joshua; Funding acquisition: Daniel Onyedikachi Ugwu; Investigation: Daniel Onyedikachi Ugwu, Prisca Oluchi Ogumba; Methodology: Daniel Onyedikachi Ugwu, Sunday Ewele Obalum, Obioma Uzoma Njoku; Resources: Daniel Onyedikachi Ugwu, Ndeari King Dedan; Software: Prisca Oluchi Ogumba, Sunday Ewele Obalum; Supervision: Parker Elijah Joshua, Obioma Uzoma Njoku; Validation: Sunday Ewele Obalum, Parker Elijah Joshua, Obioma Uzoma Njoku; Visualization: Sunday Ewele Obalum; Writing – original draft: Daniel Onyedikachi Ugwu; Writing – review & editing: Prisca Oluchi Ogumba, Sunday Ewele Obalum. All authors have read and agreed to the published version of the manuscript.

Funding

The authors thank the Federal Ministry of Education and Research (BMBF) and the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) for providing the funding in the form of a grant that made this research possible.

Declarations

Conflicts of Interest: No potential conflict of interest was reported by the author(s).

Institutional/Ethical Approval: Not applicable.

Data Availability/Sharing: The datasets used and analyzed during the current study will be made available from the corresponding author upon a reasonable request.

Supplementary Information Availability: Not applicable.

Declaration of Generative AI and AI-assisted technologies in the writing process: During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

Adegbite, A. O., & Olatunji, O. S. (2022). Assessment of soil physical degradation in tropical agroecosystems: A case study from southwestern Nigeria. *Catena, 213*, 106168. https://doi.org/10.1016/j.catena.2022.106168

Adhikari, D., Kobashi, Y., Kai, T., Kawagoe, T., Kubota, K., Araki, K., & Kubo, M. (2018). Suitable soil conditions for tomato cultivation under an organic farming system. *Journal of Agricultural Chemistry and Chemistry, 7*(3), 117–132. https://doi.org/10.4236/jacen.2018.73011

Ahmad, A. L., Ismail, S., & Bhatia, S. (2003). Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination, 157*, 87–95. https://doi.org/10.1016/S0011-9164(03)00387-4

Anele, B. C., Okorite, G. W., Chikwem, F., Anioke, F. C., & Ede, P. C. (2025a). Assessment of palm oil mill effluent-induced alterations on soil physico-chemical dynamics in Umuapu, Imo State. *SSR Journal of Multidisciplinary, 2*(5), 14–20.

Anele, B. C., Okorite, G.-W., & Chikwem, F. (2025b). Microbial dynamics of soil impacted by palm oil mill effluent in Umuapu, Imo State, Nigeria. *SSR Journal of Multidisciplinary, 2*(4), 1–7. https://doi.org/10.5281/zenodo.15814869

Anwar, M. M., & Arshad, M. (2015). Leaching losses of nutrient cations (K^+, Ca^{2+}, and Mg^{2+}) from Oxisol and Ultisol under different rates of acidic deposition in Thailand. *Journal of Soil Science and Environmental Management, 6*(5), 125–132. https://doi.org/10.14233/ajchem.2015.18072

Baiyeri, P. K., Ugese, F. D., Obalum, S. E., & Nwobodo, C. E. (2020). Agricultural waste management for horticulture revolution in sub-Saharan Africa. *CAB Reviews, 15*(017). https://doi.org/10.1079/PAVSNNR202015017

Bassey, O. I. (2016). Overview of oil palm production in Nigeria, comparative social and environmental impacts: The case of Ekong Anaku community in Cross River State, Nigeria. *Institute of Social Science, Erasmus University of Rotterdam, The Hague, Netherlands, 3*(15), 1–10.

Boateng, L., Ansong, R., Owusu, W. B., & Steiner-Asiedu, M. (2016). Coconut oil and palm oil's role in nutrition, health and national development: A review. *Ghana Medical Journal, 50*(3), 189–196. https://doi.org/10.4314/gmj.v50i3.11

Bremner, D. C., & Mulvaney, J. M. (1982). Total nitrogen. In A. L. Page, R. H. Miller, & D. R. Keaney (Eds.), *Methods of soil analysis* (Vol. 9, Part 2). American Society of Agronomy.

Cohen, G. J., Dembiec, D., & Marcus, J. (1970). Measurement of catalase activity in tissue extracts. *Analytical Biochemistry, 34*(1), 30–38. https://doi.org/10.1016/0003-2697(70)90083-7

Dushoff, I. M., Payne, J., Hershey, F. B., & Donaldson, R. C. (1965). Oxygen uptake and tetrazolium reduction during skin cycle of the mouse. *American Journal of Physiology–Legacy Content, 209*(1), 231–235. https://doi.org/10.1152/ajplegacy.1965.209.1.231

Dvořáčková, H., Dvořáček, J., Hueso González, P., & Vlček, V. (2022). Effect of different soil amendments on soil buffering capacity. *PloS ONE, 17*(2), e0263456. https://doi.org/10.1371/journal.pone.0263456

Enemo, D. C., Onah, M. C., Obalum, S. E., Njoku, O. M., & Igwe, C. A. (2025). Organic matter influence on particle density of low-activity-clay tropical soils and the implications for their porosity assessment. *International Journal of Environmental Science & Technology, 22*, 12507–12516. https://doi.org/10.1007/s13762-025-06383-8

Eno, E. O., Antai, S. P., & Tiku, D. R. (2017). Microbiological and physicochemical impact of palm oil mill effluent on the surrounding soil at selected factory location within Calabar and Uyo. *Imperial Journal of Interdisciplinary Research, 3*(10), 760–773.

Evanylo, G. (2024). Basic soil fertility and nutrient mobility. In *Urban Nutrient Management Handbook* (Chapter 4). Virginia Department of Conservation and Recreation. URL: www.dcr.virginia.gov/soil-and-water/document/nmtmscbsf.pdf

Eze, C. N., Odoh, C. K., Eze, E. A., Orjiakor, P. I., Enemuor, S. C., & Okobo, U. J. (2018). Chromium (III) and its effects on soil microbial activities and phytoremediation potentials of *Arachis hypogea* and *Vigna unguiculata*. *African Journal of Biotechnology, 17*(38), 1207–1214. https://doi.org/10.5897/AJB2018.16566

Farahani, E. (2025). Potassium may have remarkable dispersive effect on soil structure. *Open Access Journal of Agricultural Research, 10*(1), Article 000383. https://doi.org/10.23880/oajar-16000383

Gee, G. W., & Bauder, J. W. (1986). Particle size analysis. In A. Klute (Ed.), *Methods of soil analysis* (Part A, 2nd ed., Vol. 9, pp. 383–411). American Society of Agronomy, Madison, WI.

Gunn, P. (2014). Problem and prospect of small-scale palm oil processing in Delta State, Nigeria. *Biological Agriculture and Healthcare, 4*(20), 170–174.

Hashiguchi, Y., Zakaria, M. R., Toshinari, M., Yusoff, M. Z. M., Shirai, Y., & Hassan, M. A. (2021). Ecotoxicological assessment of palm oil mill effluent final discharge by zebrafish (*Danio rerio*) embryonic assay. *Environmental Pollution, 277*, 116780. https://doi.org/10.1016/j.envpol.2021.116780

Heinen, M. (2017). Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. *Communications in Soil Science and Plant Analysis, 48*(1), 1–27. https://doi.org/10.1080/00103624.2017.1407429

Hosseini, S. E., & Abdul Wahid, M. (2015). Pollutants in palm oil production process. *Journal of the Air and Waste Management Association, 65*(7), 773–781. https://doi.org/10.1080/10962247.2013.873092

Iqbal, S., Begum, F., Nguchu, B. A., Claver, U. P., & Shaw, P. (2025). The invisible architects: Microbial communities and their transformative role in soil health and global climate changes. *Environmental Microbiome, 20*, Article 36. https://doi.org/10.1186/s40793-025-00694-6

Isermeyer, H. (1952). Eine einfache Methode zur Bestimmung der Bodenatmung und der Karbonate im Boden. *Zeitschrift für Pflanzenernährung, Düngung, Bodenkunde, 56*(1–3), 26–38. https://doi.org/10.1002/jpln.19520560107

Izah, S. C., & Ohimain, E. I. (2016). Assessment of the effect of palm oil mill effluent on soil properties. *Biotechnology Research, 2*(2), 132–141. https://doi.org/10.1007/s40868-016-0012-3

Jidere, C. M., Ezeokoye, C. S., Ayah, F. T., Obalum, S. E., & Ukaegbu, E. P. (2025). Soil structure stability and organic carbon distribution along the toposequence of Orumba North in derived savannah of the South-East, Nigeria. *Nigerian Journal of Soil Science, 34*(2), 34–42. https://doi.org/10.59327/njss.2025.34.2.419

Joseph, P. O., Abraham, L. E., Jidere, C. M., Ugwuoju, C. L., & Obalum, S. E. (2025). Long-term influence of coal mining activities on physico-chemical and hydraulic properties of sandy tropical soils. *AgroEnvironmental Sustainability, 3*(2), 119–129. https://doi.org/10.59983/s2025030204

Komilis, P. D., Karatzas, E., & Halvada, C. P. (2005). The effect of olive mill wastewater on seed germination after various pretreatment techniques. *Journal of Environmental Management, 74*, 339–348. https://doi.org/10.1016/j.jenvman.2004.09.009

Kumar, S. I., Chaudhuri, S., & Maiti, I. S. K. (2013). Soil dehydrogenase enzyme activity in natural and mine soil—A review. *Middle East Journal of*

Scientific Research, 13(7), 898–906. https://doi.org/10.5829/idosi.mejsr.2013.13.7.2801

Landon, J. R. (1991). *Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics.* Longman Scientific and Technical, Essex, New York, p. 474.

Liu, J., Xie, J., Chu, Y., Sun, C., Chen, C., & Wang, Q. (2008). Combined effect of cypermethrin and copper on catalase activity in soil. *Journal of Soils and Sediments, 8*, 327–332. https://doi.org/10.1007/s11368-008-0029-x

Maduwuba, M. C. (2024). Microbiological and physicochemical evaluation of palm oil mill effluent (POME) contaminated soil. *World Scientific News, 189*, 200–211.

Margesin, R., Feller, G., Hämmerle, M., Stegner, U., & Schinner, F. (2002). A colorimetric method for the determination of lipase activity in soil. *Biotechnology Letters, 24*, 27–33. https://doi.org/10.1023/A:1013801131553

Martínez-Alvarez, V., González-Ortega, M. J., Martin-Gorriz, B., Soto-García, M., & Maestre-Valero, J. F. (2018). Seawater desalination for crop irrigation—Current status and perspectives. In *Emerging technologies for sustainable desalination handbook* (pp. 461–492). https://doi.org/10.1016/B978-0-12-815818-0.00014-X

McCauley, A., Jones, C., & Olson-Rutz, K. (2017). *Soil pH and organic matter. Nutrient management module No. 8.* U.S. Department of Agriculture (USDA), Montana State University, and Montana State University Extension.

McLean, E. O. (1982). Soil pH and lime requirement. In A. L. Page (Ed.), *Methods of soil analysis. Part 2* (2nd ed., pp. 199–224). Agronomy Monograph No. 9, ASA, Madison, WI.

Mohammad, S., Baidurah, S., Kobayashi, T., Ismail, N., & Leh, C. P. (2021). Palm oil mill effluent treatment processes—A review. *Processes, 9*(5), 739. https://doi.org/10.3390/pr9050739

Mukherjee, A., & Lal, R. (2014). Comparison of soil quality index using three methods. *PLOS ONE, 9*(8), e105981. https://doi.org/10.1371/journal.pone.0105981

Nasrin, A. B., & Hassan, M. A. (2020). Effects of palm oil mill effluent on soil chemical properties and microbial biomass. *Environmental Monitoring and Assessment, 192*, Article 456. https://doi.org/10.1007/s10661-020-08434-2

Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon and organic matter. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis. Part 2: Chemical and microbiological properties* (pp. 539–579). ASA, Madison, WI.

Nta, S. A., Udom, I. J., & Udo, S. O. (2020). Investigation of palm oil mill effluent pollution impact on groundwater quality and agricultural soils. *Asian Journal of Environment and Ecology, 12*(1), 28–36. https://doi.org/10.9734/ajee/2020/v12i130151

Nwachukwu, J. N., Njoku, U. O., Agu, C. V., Okonkwo, C. C., & Obidiegwu, C. J. (2018). Impact of palm oil mill effluent (POME) contamination on soil enzyme activities and physicochemical properties. *Research Journal of Environmental Toxicology, 12*(1), 34–41. https://doi.org/10.3923/rjet.2018.34.41

Nwaogu, L. A., Agha, N. C., & Ihejirika, C. E. (2012). Investigation on the long-term effects of palm oil mill effluent pollution on soil catalase activity and dehydrogenase activity of soil microorganisms. *Journal of Biodiversity and Environmental Sciences, 2*(4), 10–14.

Nwoko, C. O., Ogunremi, S., Nkwocha, E. E., & Nnorom, I. C. (2010). Evaluation of phytotoxicity effect of palm oil mill effluent and cassava mill effluent on tomato (*Lycopersicum esculentum*) after pretreatment option. *International Journal of Environmental Science and Development, 1*, 67–72. https://doi.org/10.7763/IJESD.2010.V1.14

Nwoko, O. C., Onoh, P. C., & Ogunyemi, S. (2012). Plant nutrient recovery following palm oil mill effluent soil amendment in maize (*Zea mays*) grown screen house experiment. *International Journal of Agriculture and Rural Development, 15*(2), 1109–1118.

Nwuche, C. O., Aoyagi, H., & Ogbonna, J. C. (2013). Lipase production from palm oil mill effluent by *Aspergillus terreus* immobilized on *Luffa* sponge. *Journal of Applied Sciences, 13*(24), 5661–5671. https://doi.org/10.3923/jas.2013.5661.5671

Nzeka, U. M. (2014). *Nigeria provides export market for oilseeds and products.* In GAIN Report, USDA Foreign Agricultural Service.

Obalum, S. E., & Obi, M. E. (2013). Moisture characteristics and their point pedotransfer functions for coarse-textured tropical soils differing in structural degradation status. *Hydrological Processes, 27*(19), 2731–2735. https://doi.org/10.1002/hyp.9398

Obalum, S. E., Chibuike, G. U., Peth, S., & Ouyang, Y. (2017). Soil organic matter as sole indicator of soil degradation. *Environmental Monitoring and Assessment, 189*, 1–19. https://doi.org/10.1007/s10661-017-5881-y

Obalum, S. E., Nwite, J. C., Watanabe, Y., Igwe, C. A., & Wakatsuki, T. (2012a). Comparative topsoil characterization of sawah rice fields in selected inland valleys around Bida, north-central Nigeria: Physicochemical properties and fertility status. *Tropical Agriculture and Development, 56*(2), 39–48. https://doi.org/10.11248/jsta.56.39

Obalum, S. E., Oppong, J., Igwe, C. A., Watanabe, Y., & Obi, M. E. (2013a). Spatial variability of uncultivated soils in derived savanna. *International Agrophysics, 27*(1), 57–67. https://doi.org/10.2478/v10247-012-0068-9

Obalum, S. E., Watanabe, Y., Igwe, C. A., Obi, M. E., & Wakatsuki, T. (2013b). Improving on the prediction of cation exchange capacity for highly weathered and structurally contrasting tropical soils from their fine-earth fractions. *Communications in Soil Science and Plant Analysis, 44*(12), 1831–1848. https://doi.org/10.1080/00103624.2013.790401

Obalum, S. E., Watanabe, Y., Igwe, C. A., Obi, M. E., & Wakatsuki, T. (2012b). Carbon stock in the solum of some coarse-textured soils under secondary forest, grassland fallow and bare footpath in the derived savanna of southeastern Nigeria. *Soil Research, 50*(2), 157–166. https://doi.org/10.1071/SR11096

Oguike, P. C., Onwuka, B. M., & Obalum, S. E. (2023). Soil organic matter control of water transmission properties of coarse-textured soils under contrasting land-use types in tropical rainforest. *International Journal of Hydrology Science and Technology, 16*(1), 93–106. https://doi.org/10.1504/IJHST.2022.10046853

Ogumba, P. O., Obalum, S. E., & Uzoh, I. M. (2020). Soil biochemical and microbial properties of sandy loam Ultisols as affected by some tillage and nutrient management practices. *International Journal of Agriculture and Rural Development, 23*(2), 5184–5195.

Ogunbode, T. O., Aliku, O., Ogungbile, P. O., Olatubi, I. V., Adeniyi, V. A., & Akintunde, E. A. (2022). Environmental impact of oil palm processing on some properties of the on-site soil in a growing city in Nigeria. *Frontiers in Environmental Science, 10*, Article 918478. https://doi.org/10.3389/

fenvs.2022.918478

Ohimain, E. I., Emeti, C. I., & Izah, S. C. (2014). Employment and socioeconomic effects of semi-mechanized palm oil mill in Bayelsa State, Nigeria. *Asian Journal of Agricultural Extension, Economics and Sociology, 3*(3), 206–216. https://doi.org/10.9734/AJAEES/2014/9197

Okolo, C. C., Okolo, E. C., Nnadi, A. L., Obikwelu, F. E., Obalum, S. E., & Igwe, C. A. (2019). The oil palm (*Elaeis guineensis* Jacq): Nature's ecological endowment to Eastern Nigeria. *Agro-Science, 18*(3), 48–57. https://doi.org/10.4314/as.v18i3.9

Okorie, E. E., Obalum, S. E., & Singh, L. (2017). The potential of fermented cottonseed oil-mill effluent as inexpensive biofertilizers and its agronomic evaluation on medium-textured tropical soil. *International Journal of Recycling of Organic Waste in Agriculture, 6*(2), 117–124. https://doi.org/10.1007/s40093-017-0158-6

Olsen, S. R., & Sommers, L. E. (1982). Determination of available phosphorus. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis* (Vol. 2, p. 403). American Society of Agronomy, Madison, WI.

Omoregie, A. I., Muda, K., Rahman, M. R., Bakri, M. K. B., Ngu, L. H., Ong, D. E. L., Basri, H. F. B., Hong, C. Y., & Mokhter, M. A. (2024). Impact of palm oil mill effluent as an economic medium for soil fixation via microbially induced carbonate precipitation. *Biomass Conversion and Biorefinery, 14*, 16369–16401. https://doi.org/10.1007/s13399-023-03889-4

Onyia, C. O., Uyub, A. M., Akuma, J. C. L., Norulaimi, N. A., & Omat, A. K. M. (2001). Increasing the fertilizer value of palm oil mill sludge: Bioaugmentation in nitrification. *Water Science and Technology, 44*(10), 157–162. https://doi.org/10.2166/wst.2001.0608

Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Chemical fertilizers and their impact on soil health. In G. H. Dar, R. A. Bhat, M. A. Mehmood, & K. R. Hakeem (Eds.), *Microbiota and biofertilizers* (Vol. 2). Springer, Cham. https://doi.org/10.1007/978-3-030-61010-4_1

Pulido-Moncada, M., Ball, B. C., Gabriels, D., Labo, D., & Cornelius, W. M. (2015). Evaluation of soil physical quality index, S, for some tropical and temperate medium-textured soils. *Soil Science Society of America Journal, 79*(1), 9–20. https://doi.org/10.2136/sssaj2014.06.0259

Rhoades, J. D. (1982). Cation exchange capacity. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis: Part 2, Chemical and microbiological properties* (pp. 149–157). American Society of Agronomy, Madison, WI.

Sharifah, M., Baidurah, S., Kobayashi, T., Ismail, N., & Leh, C. P. (2021). Palm oil mill effluent treatment processes—A review. *Processes, 9*(5), 739. https://doi.org/10.3390/pr9050739

Tabatabai, M. A. (1982). Soil enzymes: Dehydrogenases. In *Methods of soil analysis* (Part 2, pp. 903–948). American Society of Agronomy, Madison, WI.

Taye, B., & Yifru, A. (2010). Assessment of soil fertility status with depth in wheat growing highlands of Southeast Ethiopia. *World Journal of Agricultural Science, 6*, 525–531.

Thomas, G. W. (1982). Exchangeable cations. In A. L. Page (Ed.), *Methods of soil analysis. Part 2: Chemical and microbiological properties* (2nd ed., Agronomy Monograph No. 9, pp. 159–165). American Society of Agronomy.

Ugwu, D. O., Joshua, P. E., Obalum, S. E., Dedan, N. K., & Njoku, O. U. (2024). Aging-associated fermentation of palm oil-mill effluent enhances its organo-fertilizer value and the desired agronomic effects in low-fertility soils. *International Journal of Recycling of Organic Waste in Agriculture, 13*(4), 132439. https://doi.org/10.57647/ijrowa-xqpd-6789

Ugwu, D. O., Ogumba, P. O., Joshua, E. P., Obalum, S. E., & Njoku, O. U. (2025). Influence of fresh and aged palm oil-mill effluents on soil biochemical and microbial properties in humid tropical environments. *International Journal of Environment and Waste Management.* (In press).

Umoren, A. S., Igwenagu, C. M., Ezeaku, P. I., Ezenne, G. I., Obalum, S. E., Gyang, B. D., & Igwe, C. A. (2019). Long-term effects of crude oil spillage on selected physicochemical properties including heavy metal contents of sandy tropical soil. *Bulletin of Environmental Contamination and Toxicology, 102*, 468–476. https://doi.org/10.1007/s00128-019-02579-0

Wang, L., Hamel, C., Lu, P., Wang, J., Sun, D., Lee, S. J., & Gan, G. Y. (2023). Using enzyme activities as an indicator of soil fertility in grassland—An academic dilemma. *Frontiers in Plant Science, 14*, 1175946. https://doi.org/10.3389/fpls.2023.1175946

Xie, K., Cakmak, I., Wang, S., Zhang, F., & Guo, S. (2021). Synergistic and antagonistic interactions between potassium and magnesium in higher plants. *The Crop Journal, 9*(2), 249–256. https://doi.org/10.1016/j.cj.2020.10.005

Zalewska, M., Wierzbowska, J., & Nogalska, A. (2023). Effect of basic cation saturation ratios on the Mg, K, and Ca content of annual ryegrass (*Lolium multiflorum* L.). *Journal of Elementology, 28*(2), 345–360.

Zhao, C., Miao, Y., Yu, C., Zhu, L., Wang, F., Jiang, L., Hui, D., & Wan, S. (2016). Soil microbial community composition and respiration along an experimental precipitation gradient in a semiarid steppe. *Scientific Reports, 6*(1), 24317. https://doi.org/10.1038/srep24317

Zhong, S., Zeng, H., & Jin, Z. (2015). Soil microbiological and biochemical properties as affected by different long-term banana-based rotations in the tropics. *Pedosphere, 25*(6), 868–877. https://doi.org/10.1016/S1002-0160(15)30067-9

Zulfahmi, I., Batubara, A. S., Perdana, A. W., Roza, Z. H., Nafis, B., & Maghfiriadi, F. (2023). Turbidity effect derived from palm oil mill effluent altered predation period of Siamese fighting fish (*Betta splendens*, Regan 1910). *Depik, 12*(3), 398–402. https://doi.org/10.13170/depik.12.3.34628

Zulfahmi, I., Kandi, R. N., Huslina, F., Rahmawati, L., Muliari, M., Sumon, K. A., & Rahman, M. M. (2021). Phytoremediation of palm oil mill effluent (POME) using water spinach (*Ipomoea aquatica* Forsk). *Environmental Technology and Innovation, 21*, 101260. https://doi.org/10.1016/j.eti.2020.101260