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Ecological valorization of palm oil mill effluent suspended solids: Enhancing soil chemical functions and physiological performance of oil palm

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ABSTRACT

This study evaluated the effects of suspended solids derived from palm oil mill effluent (POME) on soil chemical properties, nutrient uptake, physiological responses, and early performance of immature oil palm. The experiment was conducted from June 2024 to March 2025 at PT Bumitama Gunajaya Agro (BGA), Central Kalimantan, Indonesia, using a randomized complete block design with two treatments: solid POME application (25 kg plant^{-1}) and a non-solid control, both receiving identical inorganic fertilization. Agronomic, biochemical, plant nutrient, and soil chemical parameters were assessed six months after application. Solid POME markedly improved soil organic carbon, cation exchange capacity, available and total nutrients, and exchangeable base cations, resulting in clear treatment separation in PCA, with the first component explaining over 80% of total variance. These improvements enhanced nutrient accumulation in frond and leaflet tissues, particularly N, P, K, and Ca, indicating improved nutrient uptake and internal allocation. Vegetative growth responses were limited at this early stage; however, solid POME significantly increased the number of female inflorescences, suggesting stimulation of early reproductive differentiation. Physiologically, solid POME reduced oxidative stress, as evidenced by lower SOD, POD, proline, and MDA levels, while increasing catalase and nitrate reductase activity, reflecting improved metabolic stability. Correlation analysis confirmed strong linkages between improved soil fertility, enhanced nutrient status, and reduced physiological stress. Overall, suspended solid POME functioned as an effective soil conditioner, enhancing soil fertility, nutrient use efficiency, and physiological stability of oil palm grown on marginal soils.

Keywords: oil palm, suspended solids, POME, agronomy, biochemistry, soil quality.

INTRODUCTION

Oil palm plantations generate substantial volumes of palm oil mill effluent (POME), a nutrient-rich organic by-product resulting from the wet processing of fresh fruit bunches. POME is widely recognized as one of the most challenging waste streams in the palm oil industry due to its high organic load and nutrient content, but it also represents a significant opportunity for resource recovery and circular bioeconomy applications (Imam et al., 2025; Loh et al., 2019). Among the various fractions of POME, suspended solids (POME sludge) contain high concentrations of organic carbon, nitrogen, phosphorus, potassium, and essential micronutrients, as well as humic-like substances and partially decomposed organic compounds (Mutar et al., 2025). These constituents impart favorable physicochemical properties, including high cation exchange capacity, buffering potential, and water-holding capacity, positioning POME suspended solids as a promising organic soil amendment within tropical plantation systems (Loh et al., 2019; Ngone et al., 2023).

From an ecological engineering perspective, the utilization of POME suspended solids represents a strategic approach to transforming an environmental liability into a functional resource that supports soil rehabilitation, nutrient cycling, and sustainable plantation management (Imam et al., 2025; Yusuf et al., 2025). The valorization of POME aligns with sustainability goals by reducing waste discharge, minimizing reliance on synthetic fertilizers, and enhancing ecosystem services within oil palm agroecosystems (Yusuf et al., 2025).

This potential is particularly relevant in Southeast Asia, where oil palm cultivation is predominantly established on highly weathered tropical soils that are inherently constrained by low organic matter content, limited nutrient retention, high leaching losses, and weak aggregate stability (Boafo et al., 2020; Comte et al., 2013). Such soils often exhibit rapid nutrient depletion following mineral fertilizer application, leading to inefficient nutrient use and inconsistent early growth of young oil palm. Organic amendments derived from POME suspended solids may mitigate these limitations by increasing soil organic carbon pools, enhancing nutrient sorption capacity, and improving soil structure, thereby creating a more favorable rhizosphere environment for root development and nutrient acquisition (Lisan et al., 2025; Ngone et al., 2023).

Beyond direct nutrient supply, POME suspended solids may exert indirect effects on plant performance through their influence on soil biological activity and biogeochemical processes. The addition of organic substrates can stimulate microbial biomass and enzymatic activity, accelerating nutrient mineralization while simultaneously promoting microbial immobilization that moderates nutrient release (Sanches et al., 2024). This dual function contributes to a more synchronized nutrient supply relative to plant demand, which is particularly critical during the early establishment phase of oil palm (Ngone et al., 2023). Improved soil biological functioning may also enhance the production of plant growth–promoting substances and improve root–microbe interactions, further supporting nutrient uptake efficiency and physiological stability (Sanches et al., 2024; Supriatna et al., 2023).

Plant responses to organic soil conditioners are best understood through a combination of agronomic, physiological, and biochemical indicators. While growth traits reflect integrated outcomes of resource availability, biochemical markers provide early and sensitive signals of plant functional status (Aina et al., 2024; Loh et al., 2019; Schönbeck et al., 2023). Chlorophyll content is directly linked to nitrogen availability and photosynthetic capacity, whereas nitrate reductase activity reflects the plant's ability to assimilate inorganic nitrogen into organic forms (Chamizo-Ampudia et al., 2017; Supriatna et al., 2023). Proline accumulation and antioxidant enzyme systems play critical roles in maintaining cellular homeostasis by mitigating oxidative stress associated with fluctuating nutrient and moisture conditions (Ngone et al., 2023; Zulfiqar and Ashraf, 2023). Lipid peroxidation, quantified as malondialdehyde, serves as an integrative indicator of membrane integrity and stress-induced damage (Rawat et al., 2021; Sanches et al., 2024). Evaluating these parameters together allows for a mechanistic interpretation of how suspended solids influence physiological resilience and metabolic efficiency.

At the soil level, the effects of POME suspended solids are inherently multivariate and interconnected (Tambe et al., 2024). Changes in soil pH can modify nutrient solubility and microbial activity, while increases in organic matter influence nutrient retention, moisture dynamics, and buffering capacity (Bashir et al., 2021; Wang and Kuzyakov, 2024). Complex interactions between organic matter decomposition, microbial transformation, and soil mineral surfaces further regulate the availability of nitrogen, phosphorus, and potassium. Principal component analysis (PCA) offers a powerful tool to disentangle these interactions by identifying dominant gradients of soil chemical change and highlighting the variables that most strongly drive shifts in soil fertility status. Such multivariate insights are essential for ecological engineering studies, where system-level responses are often more informative than single-variable comparisons.

Plant tissue nutrient concentrations in leaves, fronds, and rachis integrate soil nutrient availability over time and provide insight into internal nutrient allocation and transport processes (Sharma et al., 2025). Differences among these tissues reflect both functional specialization and temporal dynamics of nutrient storage and remobilization in oil palm (Brant and Chen, 2015; Ollivier et al., 2017). Linking tissue nutrient data with soil chemical properties and physiological indicators enables the identification of nutrient transfer pathways and feedback mechanisms within the soil–plant continuum. Correlation analyses further strengthen this interpretation by revealing coordinated responses among soil improvement, nutrient uptake, physiological performance, and early productivity indicators.

Despite the recognized agronomic and environmental potential of POME-based organic amendments, most previous studies have focused on either soil chemical changes or plant growth responses in isolation (H et al., 2019; Hau et al., 2020; Ugwu et al., 2024). Studies in oil palm plantation systems, including those reported by Rahman et al. (2021), have demonstrated that residue management and POME application can enhance soil fertility and yield performance; however, these studies have generally relied on liquid POME fractions, as also noted by Loh et al. (2021), and have paid limited attention to plant physiological functioning. Integrated evaluations of agronomic performance, biochemical physiology, soil chemical dynamics, and plant tissue nutrient status remain relatively scarce, thereby constraining mechanistic understanding of how POME suspended solids regulate physiological resilience and metabolic efficiency at the plantation scale. This study addresses this gap by explicitly positioning plant physiological performance as the primary response variable and by evaluating POME suspended solids, a carbon- and nutrient-rich fraction that remains underexplored in oil palm plantation systems.

Therefore, this study aims to provide a comprehensive and integrated evaluation of the effects of POME suspended solids on oil palm growth, physiological performance, and soil chemical quality. By combining agronomic measurements, biochemical indicators, multivariate soil analysis, and correlation-based interpretation, this research seeks to advance the ecological engineering understanding of waste-derived organic amendments and to support the sustainable valorization of POME suspended solids in oil palm plantation ecosystems.

MATERIAL AND METHOD

Site description

This research was conducted at PT Bumitama Gunajaya Agro (BGA), Cempaga Hulu District, East Kotawaringin Regency, Central Kalimantan (-1.9940292214449042, 113.07367047068779), from June 2024 to March 2025. The study area has a tropical climate with an annual rainfall of 2500–3000 mm, an average humidity of 89%, and a mean temperature of 27 °C.

Experimental design

The experiment was arranged using a randomized complete block design (RCBD) with two treatment levels: (1) application of suspended solid organic fertilizer at a rate of 25 kg per plant, and (2) a control treatment without organic fertilizer. The selected application rate of 25 kg plant^{-1} follows the dosage used by Adiprasetyo et al. (2014), who reported that this rate represents a practical and agronomically relevant level of oil palm biomass application for enhancing soil fertility. Accordingly, the use of a single application rate of 25 kg plant^{-1} in the present study aimed to evaluate the functional soil-plant response under realistic field conditions and support sustainable nutrient management practices. The uniformity of the chemical composition of the POME solid suspension was ensured through mechanical mixing using an excavator before field application, allowing for a homogeneous distribution of the material across the treated plots. To eliminate the confounding effects of nutrient availability, both treatments received identical rates of inorganic fertilizers (urea, triple superphosphate, and potassium chloride) following the company's standard fertilization protocol. Each treatment was applied to a 30-ha plantation area. Within each treatment area, three replicate blocks were randomly established to account for spatial heterogeneity in soil and site conditions. From each block, ten representative oil palm plants were selected as experimental units for agronomic, biochemical, and soil analyses. The mean value of the sampled plants within each block was used for statistical evaluation, ensuring independence among replicates and reducing within-block variability.

Data collection

Data collected included agronomic parameters, plant biochemical responses, plant tissue element content, and soil chemical properties. Agronomic parameters observed were plant height, number of leaves, stem diameter, and number of female inflorescences. Biochemical parameters included chlorophyll content, proline, superoxide dismutase (SOD), peroxidase (POD), malondialdehyde (MDA), nitrate reductase activity (ANR), and catalase (CAT) enzyme activity. Observations were conducted six months after fertilizer application to assess the detailed effects on both soil and plant systems.

Determination of biochemical activity

Fresh leaves were washed thoroughly under running water, air-dried, and cut into small pieces. Approximately 5–10 g of leaf tissue was homogenized in liquid nitrogen using a mortar and pestle or blender together with extraction buffer (50–100 mM sodium phosphate, pH 7.0) at a ratio of 1:4 to 1:5 (w/v). The homogenate was filtered through Whatman filter paper, and the filtrate was centrifuged at 10,000–12,000 rpm for 15–20 min at 4 °C. The resulting supernatant was collected and used as the crude enzyme extract for biochemical analyses.

CAT activity was determined in a reaction mixture containing 100 µL of crude extract, 30 mM hydrogen peroxide, and 100 mM sodium phosphate buffer (pH 7.0), adjusted to a final volume of 3.0 mL. The decline in absorbance at 240 nm was monitored for 1 min using a spectrophotometer, with a blank lacking enzyme extract. One unit of CAT activity was defined as a decrease in absorbance of 0.001 min^{-1} (Hadwan and Abed, 2016).

POD activity was assayed by mixing 500 µL of crude extract with 5 mM hydrogen peroxide, 5 mM 4-methylcatechol, and sodium phosphate buffer (pH 7.0) to a final volume of 3.0 mL. Absorbance was measured at 420 nm for 1 min against a blank without extract. One unit of POD activity was defined as an increase in absorbance of 0.001 min^{-1} (Maehly, 1954).

SOD activity was assessed in a 3.0 mL reaction mixture containing 50 mM sodium phosphate buffer (pH 7.6), 0.1 mM EDTA, 50 mM sodium carbonate, 12 mM L-methionine, 50 µM NBT, 10 µM riboflavin, and 100 µL crude extract. A control without extract served as a reference. The mixtures were exposed to white light for 15 min at room temperature, and absorbance was measured at 560 nm. One unit of SOD activity was defined as the amount of enzyme required to inhibit 50% of NBT photoreduction (Alici and Arabaci, 2016).

Proline content was quantified following the procedure described by (Bates et al., 1973). Chlorophyll concentration was determined using the ethanol extraction method based on Arnon (1949), with absorbance measured at wavelengths of 645 and 663 nm. Lipid peroxidation was quantified based on malondialdehyde (MDA) accumulation. Approximately 0.2 g of fresh leaf tissue (midrib removed) was homogenized with 5 mL of 0.1% trichloroacetic acid (TCA). The homogenate was centrifuged at 10,000 g for 5 min, and the resulting supernatant was mixed with 5 mL of 20% TCA containing 0.5% thiobarbituric acid (TBA). The mixture was incubated at 95–100 °C for 30 min in a water bath and then cooled to room temperature. After cooling, samples were centrifuged at 5000 g for 10 min. Absorbance of the supernatant was measured at 523 and 600 nm. MDA content was calculated using an extinction coefficient of 1.55 M^{-1} cm^{-1} according to Hodges et al. (1999).

Nitrate reductase activity (NRA) according by Evans and Nason, (1953) was assessed in a single measurement event. Freshly excised leaf tissues were immediately placed in light-impermeable plastic tubes containing 5 mL of 0.1 M phosphate buffer and incubated in complete darkness for 24 h. Following this initial incubation, 0.1 mL of 0.05 M $NaNO_3$ was added to each tube, and samples were maintained under dark, ambient laboratory conditions for an additional 2 h. Reaction tubes were prepared separately by adding 0.2 mL of 1% sulfanilamide and 0.2 mL of 0.02% N-ethyl-1-naphthylamine. At the end of the incubation period, 0.1 mL of the sample extract was transferred into the reaction tubes and allowed to stand for 10–15 min, during which a characteristic pink coloration developed, indicating the presence of reduced nitrate. Subsequently, 2.5 mL of distilled water was added to adjust the final volume to 3 mL, followed by thorough mixing. Absorbance of the resulting solution was determined at 540 nm using a spectrophotometer. NRA was expressed as µmol NO_2^- g^{-1} h^{-1} and calculated as:

$$NRA = AS \times A0 \times FW \times T \quad (1)$$

where: *AS* is the absorbance at 540 nm, *A*0 is the absorbance of the standard solution, *FW* is the fresh weight of the tissue, and *T* is the incubation time.

Soil sampling and analysis

Soil samples were collected from the palm tree circle area (under the canopy) at a depth of 0–20 cm. Sampling was conducted before treatment (pre-application) and after the observation period to determine changes in nutrient content and other chemical properties. Soil parameters analyzed included pH, organic matter content, available N, P, and K, as well as soil texture and moisture. Laboratory analyses were performed following standard procedures established by the Soil Research Institute (2005) and applicable national standards.

Data analysis

Data were analyzed using univariate and multivariate approaches to assess the effects of suspended solid POME application. Treatment effects were evaluated using an independent-samples *t*-test ($p < 0.05$). Replicate block means were used as experimental units, and data were checked for normality and variance homogeneity prior to analysis. Growth and physiological variables were visualized using violin plots combined with boxplots to illustrate distributional differences between treatments. Multivariate variation in soil chemical properties was assessed using PCA based on standardized variables, with treatment separation visualized using 95% confidence ellipses. Relationships among soil properties, plant growth traits, nutrient concentrations, and physiological parameters were examined using correlation analysis and presented as a heatmap. Plant nutrient concentrations in fronds and leaflets were standardized and visualized using heatmaps to compare relative nutrient allocation between treatments. All analyses were performed using the R software version 4.5.1 and visualized using the RStudio platform.

RESULTS AND DISCUSSION

Soil chemical properties

Application of the solid fraction of POME markedly improved soil chemical properties compared with the non-solid treatment (Figure 1). Soils receiving solid POME exhibited higher organic carbon (C_{org}), cation exchange capacity (CEC), available phosphorus (P_{avail}), total nitrogen (N), total phosphorus (P_{tot}), and exchangeable base cations (Ca, Mg, and K). These improvements indicate a substantial enhancement of soil fertility status and nutrient-retention capacity. The increase in cation exchange capacity (CEC) is particularly significant in tropical soils, where intense rainfall and high weathering rates promote nutrient leaching and limit nutrient retention. Enhancing CEC improves the soil's ability to retain and gradually supply essential base cations to plant roots, thereby increasing nutrient-use efficiency and soil fertility sustainability. Similar improvements in soil C_{org}, CEC, and nutrient availability following the application of composted or treated palm oil mill effluent have been widely reported in tropical agricultural systems. Studies have demonstrated that POME-based composts and organic amendments substantially increase soil organic matter content, improve nutrient status, and enhance soil chemical properties in oil palm plantations and other tropical soils (Hau et al., 2020; Krishnan et al., 2017; Rahman et al., 2021; Siddiquee et al., 2017). These findings consistently confirm the effectiveness of

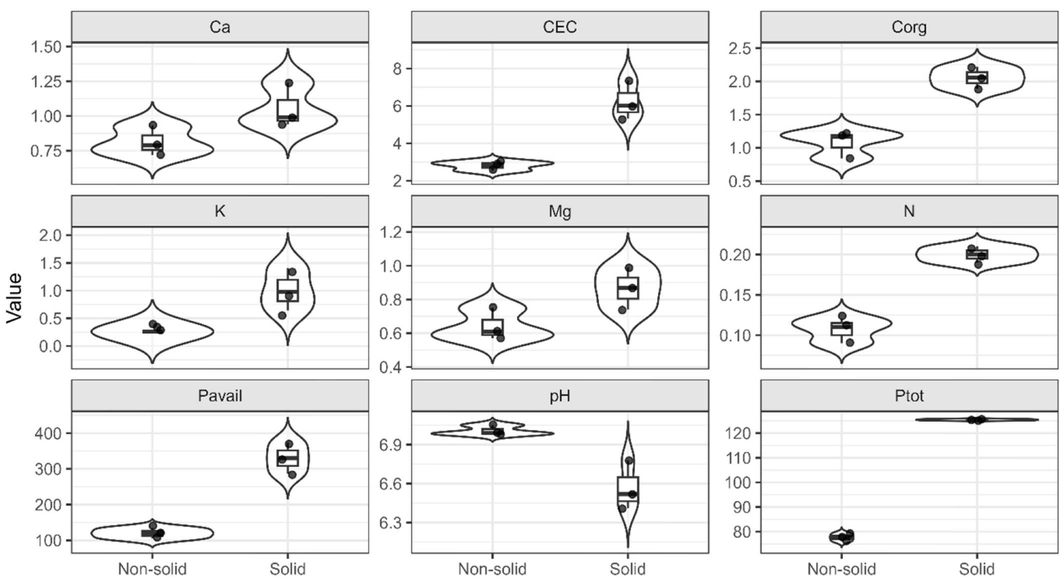

Figure 1. Soil chemical properties

POME-derived organic amendments as soil conditioners capable of mitigating nutrient leaching constraints in highly weathered tropical soils.

The addition of organic matter from solid POME increases humic substances, which contribute directly to higher CEC and improved nutrient buffering (Kabala and Jedrzejewski, 2024; Maffia et al., 2025). Second, microbial mineralization of organic compounds releases N and P gradually, increasing their availability while reducing losses through leaching (Geisseler et al., 2021). Third, organic inputs improve soil aggregation and porosity, indirectly enhancing root growth and nutrient uptake (Ray et al., 2025). Reviews on POME management by Supriatna et al. (2023) consistently emphasize that properly treated solid fractions function not only as nutrient sources but also as long-term soil quality enhancers.

Frond and leaflet nutrient content

Enhanced soil fertility under the solid POME treatment was clearly reflected in plant nutrient status. Concentrations of N, P, K, Ca, Mg, B, and Cu in both leaflet and frond tissues were generally higher under solid POME application (Figure 2 and 3). Leaflet nutrient enrichment is particularly relevant because leaflets represent the most physiologically active tissues, closely associated with photosynthesis and biomass production. Elevated leaflet N and P indicate efficient transfer of mineralized nutrients from soil to plant tissues, consistent with improved soil nutrient availability.

Frond nutrient patterns further support this interpretation, showing increased macronutrient accumulation under solid POME (Figure 2). The standardized nutrient heatmap demonstrated a clear differentiation between treatments (Figure 4). This phenomenon indicates that the application of suspended solid POME substantially modified nutrient uptake and internal allocation in young oil palm. Result consistent with findings that organic inputs with high carbon content improve soil nutrient status and plant uptake by enhancing soil chemical properties (e.g., organic carbon and CEC) that correlate positively with higher foliar nutrient levels (Nurlaeny et al., 2017). The solid treatment consistently exhibited higher standardized values for key macronutrients (N, P, and K) and secondary nutrients (Ca) in both frond and leaflet tissues, reflecting improved nutrient availability, retention, and uptake efficiency mediated by enhanced soil organic matter and cation exchange capacity (Boafo et al., 2020). This coordinated enrichment across tissues suggests a more balanced nutrient supply, which is critical for sustaining photosynthetic capacity, structural development, and metabolic activity during early growth stages. In contrast, the non-solid treatment generally showed lower standardized nutrient levels, consistent with weaker nutrient retention and greater susceptibility to leaching in highly weathered tropical soils despite uniform inorganic fertilization.

An exception was observed for Mg, which displayed relatively higher standardized values in the non-solid treatment (Figure 4). This pattern

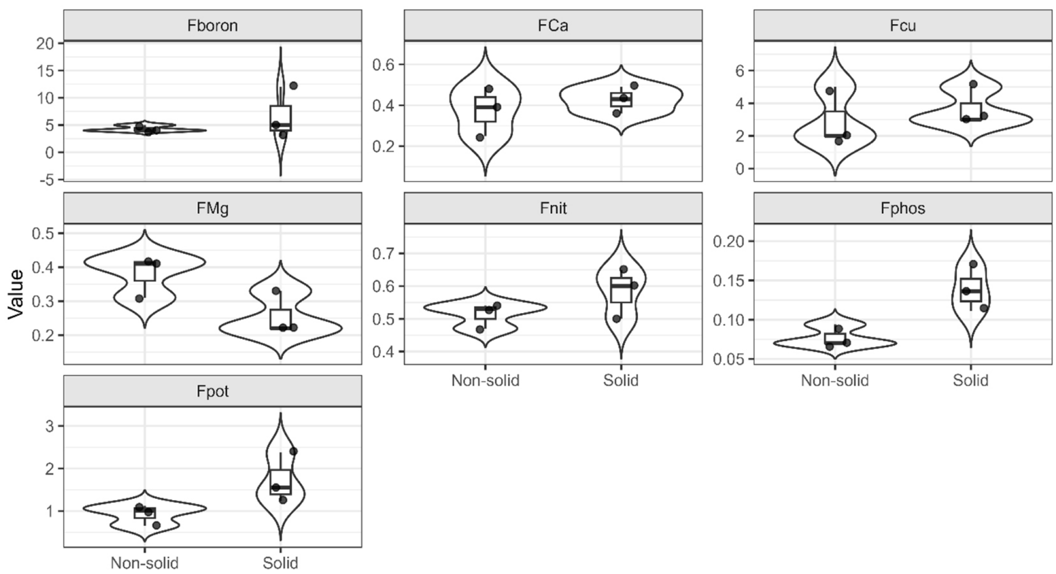

Figure 2. Frond nutrient concentration

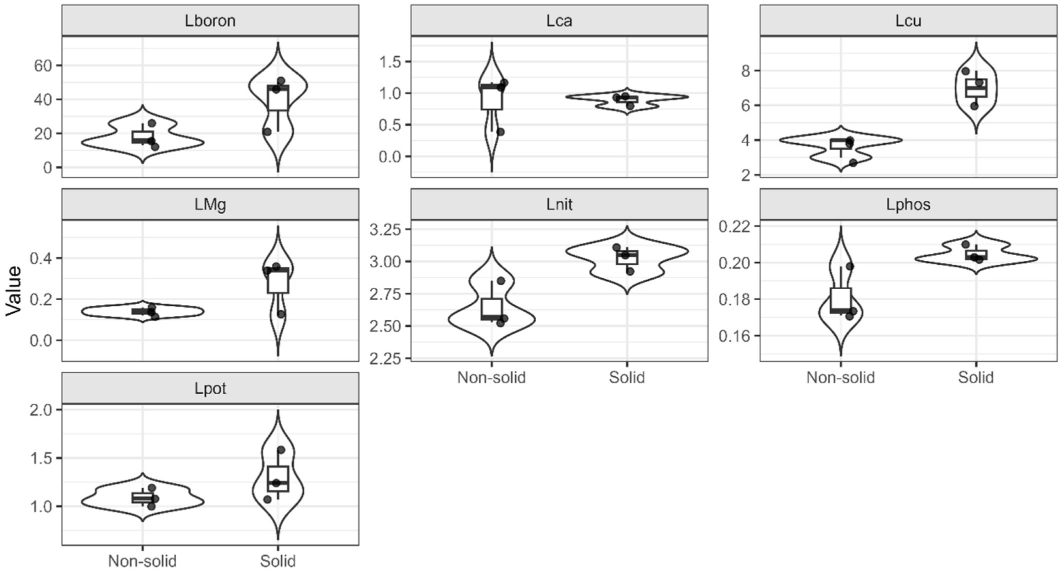

Figure 3. Leaflet nutrient concentrations

can be attributed to cation antagonism, whereby increased Ca^{2+} and K^{+} availability under the solid treatment competitively reduced Mg^{2+} uptake at root exchange sites, while lower concentrations of competing cations under the non-solid treatment favored Mg absorption. This finding is consistent with evidence that interactions among exchangeable Ca, Mg, and K influence plant uptake and can lead to antagonistic effects when cation balance is altered by soil amendments that increase CEC (Yang et al., 2024). Importantly, the elevated Mg status under non-solid conditions did not translate into improved growth or physiological performance, indicating that Mg was not a limiting factor in this system. Comparable results have been reported in studies where composted POME or organic sludge amendments increased nutrient concentrations in plant tissues, reflecting improved nutrient cycling and uptake efficiency (Cellier et al., 2014). However, some studies have reported weaker or variable responses depending on POME processing methods and application rates, highlighting the importance of controlled amendment management (Imam et al., 2025; Ngone et al., 2023) (Figure 3).

Growth responses

The violin–boxplot distributions for growth traits were nearly identical between the treated and untreated palms, indicating that vegetative structure remained largely unaffected during the first six months (Figure 5). This outcome aligns with the slow-release nature of organic amendments, which require extended time for mineralization before noticeably contributing to structural biomass accumulation. Ray et al. (2025) demonstrated that root distribution and soil responses to organic amendments became more pronounced after ≥1.5 years of application. Another likely explanation is the relatively high baseline soil fertility, particularly nitrogen and potassium, which may have already been adequate to support early vegetative development (De Corato et al., 2024; Zhao et al., 2021).

Despite minimal effects on vegetative traits, suspended solid application significantly increased the number of female inflorescences, as reflected by higher median and variability of NFF (Figure 5). This indicates preferential stimulation of early reproductive differentiation rather than

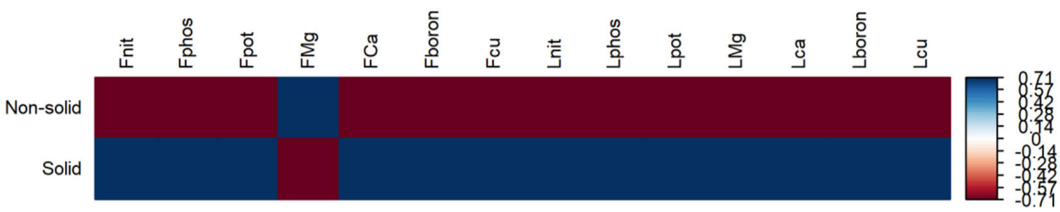

Figure 4. Standardized nutrient contents in frond and leaflet

vegetative growth. Such responses are consistent with improved soil nutrient balance, particularly P, K, Ca, and micronutrients, supplied through organic amendments acting as slow-release nutrient sources. Recent studies show that organic amendments increase soil organic carbon and cation exchange capacity, enhancing nutrient retention, buffering capacity, and rhizosphere stability during floral initiation (Xu et al., 2025). Long-term SOC accumulation further improves soil structure and nutrient availability, supporting reproductive performance in perennial crops (Liu et al., 2025). The limited response in vegetative growth parameters is attributed to the short duration of application (one year) combined with the slow-release characteristics of organic amendments. Improvements in soil fertility and plant nutritional status typically precede visible structural growth responses, especially in immature oil palm, where organic inputs require longer periods to fully translate into biomass accumulation (Suvendran et al., 2025).

Chlorophyll-related traits

Interestingly, chlorophyll concentrations (chlorophyll a, b, and total) were not consistently higher under the solid POME treatment, and in some cases were slightly higher under non-solid conditions (Figure 6). This apparent contradiction can be attributed to a "dilution effect", where increased leaf expansion and biomass under nutrient-rich conditions lower pigment concentration per unit leaf mass despite greater whole-plant photosynthetic capacity; similar mass-based chlorophyll dilution has been documented in studies linking increased leaf area with reduced chlorophyll concentration per unit tissue in high-growth conditions (Van De Velde et al., 2023; Yang et al., 2024). Conversely, under relatively lower nutrient availability, plants may allocate proportionally more chlorophyll per unit tissue as a compensatory mechanism to maintain photosynthetic efficiency (Ankaya, 2025).

Biochemical responses: proline and antioxidant enzymes

Biochemical indicators (Figure 7) revealed contrasting stress responses between treatments. Plants under non-solid conditions exhibited higher superoxide dismutase (SOD), peroxidase (POD), and proline levels, indicating elevated oxidative stress. In contrast, solid POME increased catalase (CAT) and nitrate reductase (ANR) activity while reducing stress biomarkers, reflecting improved metabolic stability. Some studies report that organic amendments alleviate oxidative stress by improving nutrient and water availability. Shahid (2021) demonstrated that organic soil amendments alleviate oxidative stress by improving soil nutrient and water availability, which reduces reactive oxygen species formation and normalizes antioxidant enzyme activities. Similarly, Shah et al. (2023) showed that organic fertilizer application enhances plant stress tolerance

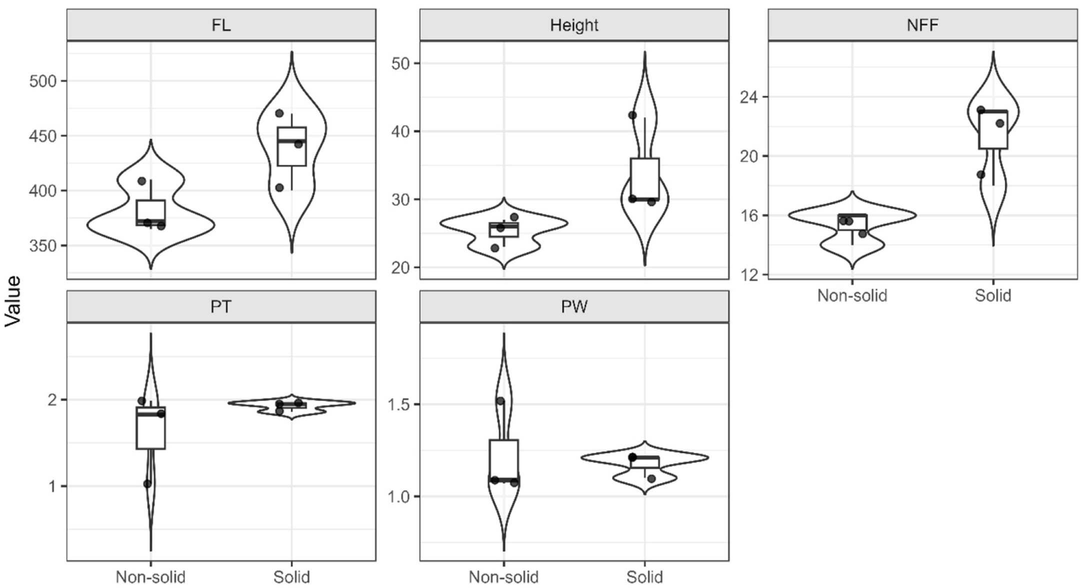

Figure 5. Growth parameters of young oil palm

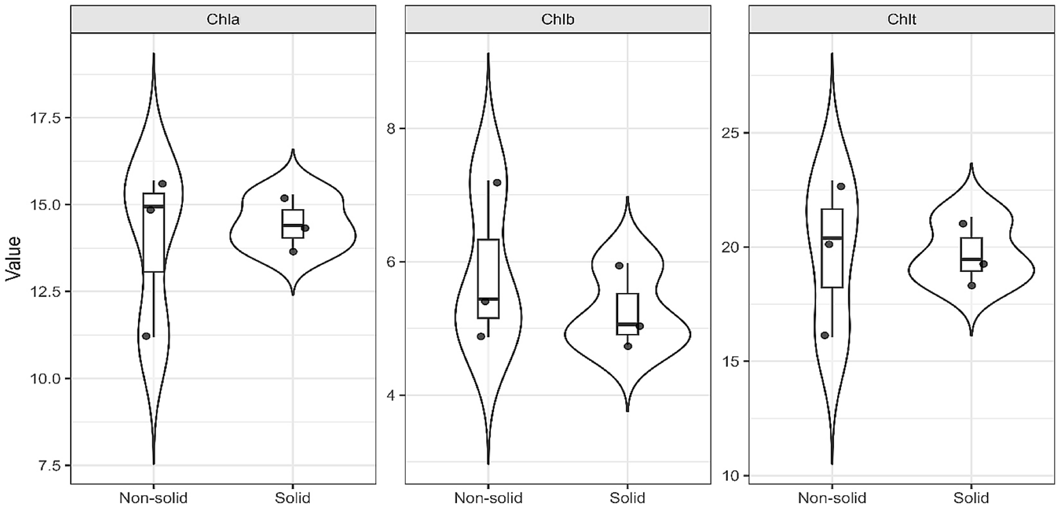

Figure 6. Chlorophyll content

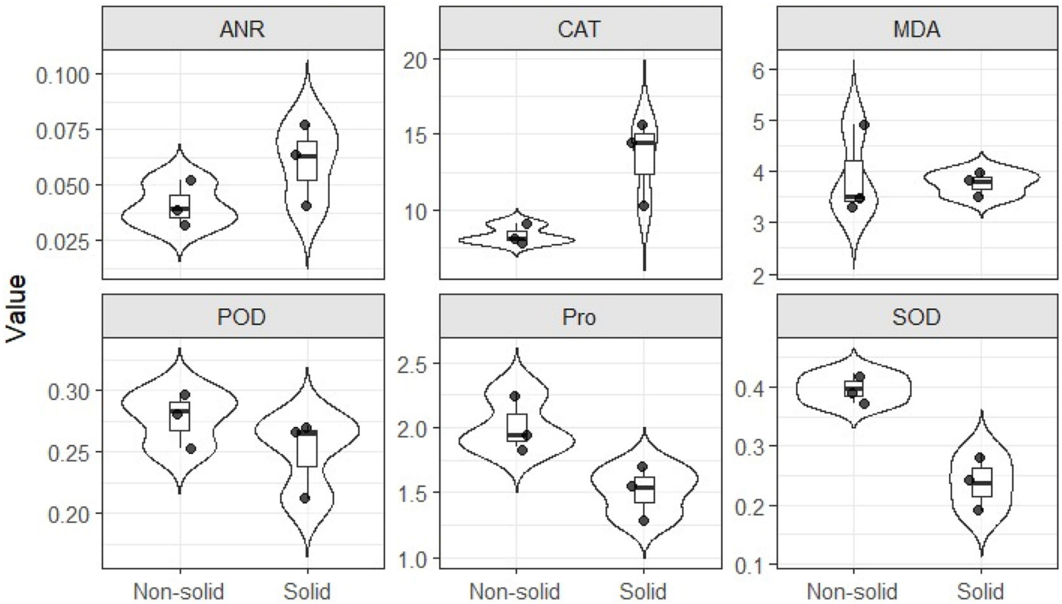

Figure 7. Proline and antioxidant enzyme activities

by modulating antioxidant defense systems and lowering stress-induced biochemical markers.

These patterns suggest that improved soil and nutrient conditions under solid POME reduce the generation of reactive oxygen species, thereby lowering the requirement for stress-induced antioxidant responses. Elevated CAT activity under solid treatment indicates more efficient hydrogen peroxide detoxification and reflects a metabolically stable growth environment (Hasanuzzaman et al., 2020). Recent studies demonstrate that organic amendments alleviate nutrient and water stress by improving soil physicochemical properties, which in turn reduces oxidative damage and normalizes antioxidant enzyme activities (Kumari et al., 2022; Liu et al., 2025). Similar responses have been observed across cropping systems, where organic inputs enhanced CAT activity while suppressing excessive SOD and POD induction (Murtaza et al., 2025). Nevertheless, transient increases in oxidative activity shortly after amendment application have also been reported, highlighting the importance of amendment maturity and application timing (Razzaq et al., 2024).

Correlation analysis

Correlation analysis provided integrative evidence linking soil improvement to plant performance (Figure 8). Soil parameters such as CEC,

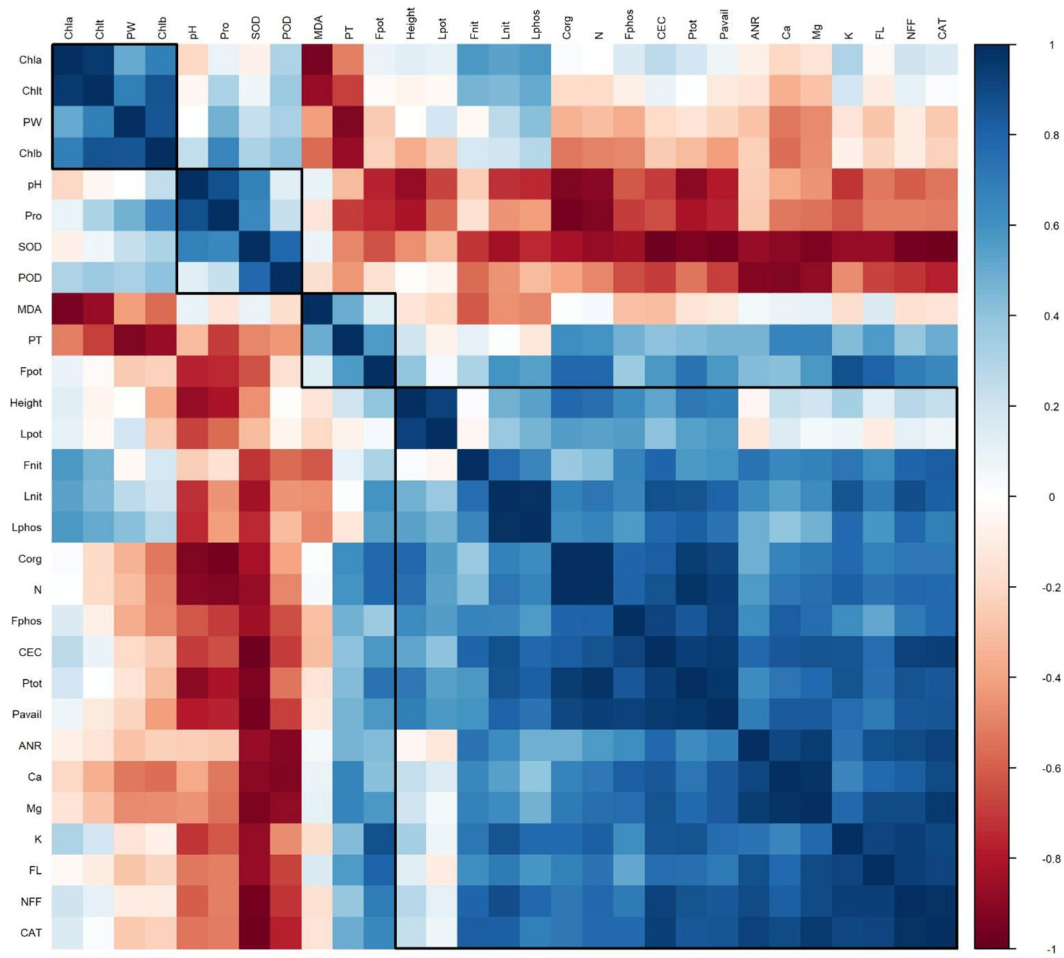

Figure 8. Correlation matrix

Corg, Pavail, Ca, Mg, N, and Ptot were strongly and positively correlated with tissue nutrient concentrations and growth traits. Conversely, antioxidant enzymes associated with stress (SOD, POD), proline, and MDA were negatively correlated with soil fertility and growth parameters. These relationships confirm that soil chemical improvement through solid POME application directly enhances nutrient uptake and growth while indirectly reducing physiological stress. This soil–plant physiology linkage has been widely reported in agroecological studies evaluating organic amendments, where improved soil chemical buffering leads to greater plant resilience and reduced metabolic stress (Avianto et al., 2024; Hasanuzzaman et al., 2020; Li et al., 2024).

Principal component analysis (PCA)

PCA clearly separated solid and non-solid treatments along the first principal component, which explained more than 80% of total variance and was strongly associated with Corg, CEC, Pavail, Ptot, Ca, and Mg (Figure 9). The solid POME treatment clustered tightly, indicating a more homogeneous and stable soil chemical environment, whereas non-solid treatments were more dispersed and associated with pH-driven variability.

This multivariate separation confirms that solid POME application induces a comprehensive shift in soil chemical status rather than isolated changes in individual properties. Similar PCA-based separations have been reported in studies evaluating organic waste amendments, reinforcing the robustness of soil quality improvement induced by organic inputs when properly managed (Boafo et al., 2020; Ngone et al., 2023; Samaei et al., 2022).

Overall, the integrated interpretation across all variables illustrates a coherent and mutually reinforcing pattern. Suspended solid enhances soil chemical properties, which subsequently improve nutrient uptake, strengthen biochemical efficiency, reduce stress responses, and ultimately translate into superior agronomic performance. This multi-layered evidence provides a robust basis for concluding that POME-derived suspended

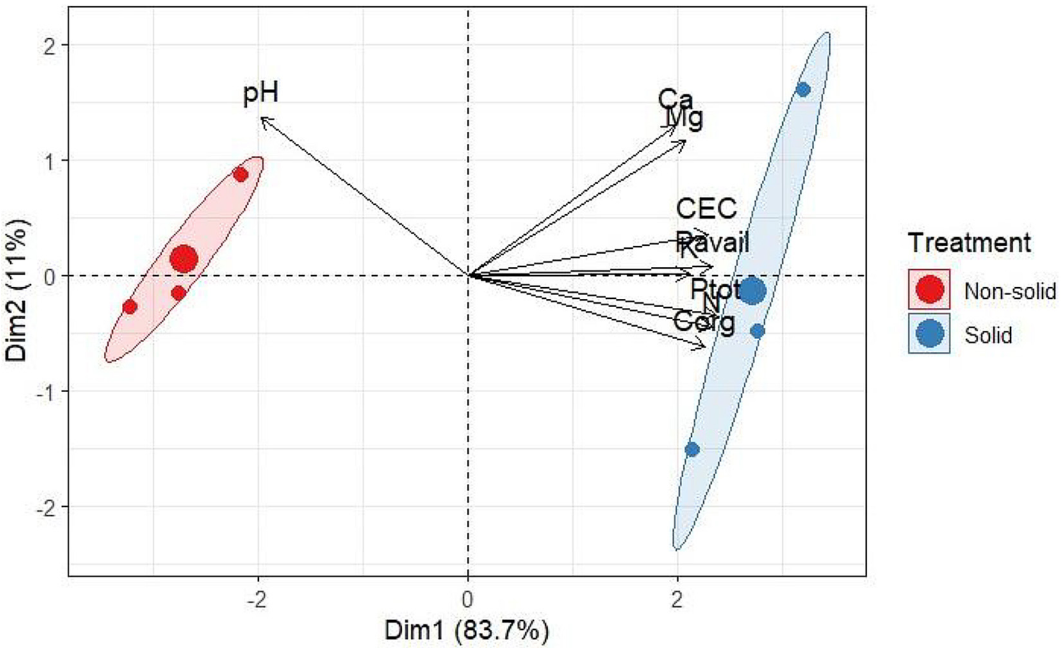

Figure 9. PCA biplot

solids act not only as fertilizers but also as effective soil conditioners capable of improving long-term soil health and plant productivity in oil palm systems. No environmental risks were observed during the study period, as reported by Elvitriana et al. (2021). However, as this research was conducted as a short-term field study, long-term monitoring is required to fully assess potential environmental impacts associated with prolonged POME solid application. The applicability of the results is currently limited to inceptisol soils under tropical microclimatic conditions in the study area. While the findings provide important insights into solid POME utilization, further studies are required to evaluate its effectiveness across different soil types and agro-ecological regions.

CONCLUSIONS

This study provides an integrated evaluation of the effects of suspended solid POME on soil quality, plant physiology, and early performance of oil palm. Solid POME markedly improved soil chemical properties, including organic carbon, CEC, and nutrient availability, leading to enhanced nutrient uptake in frond and leaflet tissues. Although vegetative growth responses were limited at the early stage, solid POME significantly increased female inflorescence production, indicating stimulation of reproductive differentiation. Improved soil conditions reduced oxidative stress, enhanced metabolic efficiency, and strengthened soil–plant linkages, as confirmed by correlation and PCA analyses. Overall, suspended solid POME functions as both a fertilizer and an effective soil conditioner supporting sustainable oil palm production.

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REFERENCES

1. Adiprasetyo, T., Purnomo, B., Handajaningsih, M., Hidayat, H. (2014). The Usage of BIOM3G-biofertilizer to improve and support sustainability of land system of independent oil palm smallholders. *International Journal on Advanced Science, Engineering and Information Technology*, *4*(5), 345 https://doi.org/10.18517/ijaseit.4.5.431
2. Aina, O., Bakare, O. O., Fadaka, A. O., Keyster, M., Klein, A. (2024). Plant biomarkers as early detection tools in stress management in food crops: A

review. *Planta*, *259*(3), 60. https://doi.org/10.1007/s00425-024-04333-1

3. Alici, E., Arabaci, G. (2016). Determination of SOD, POD, PPO and CAT enzyme activities in *Rumex obtusifolius* L. *Annual Research & Review in Biology*, *11*(3), 1–7. https://doi.org/10.9734/ARRB/2016/29809
4. Ankaya, F. (2025). Relationships between leaf structural and functional traits of urban landscape plant species: Implications for sustainable landscape planning. *BMC Plant Biology*, *25*(1), 1300. https://doi.org/10.1186/s12870-025-07363-3
5. Avianto, Y., Noviyanto, A., Jaya, G. I., Handru, A., Ferhat, A., Hartanto, E. S., Sidiq, M. F., Saputra, B. F., Ramadhani, J. N., Shofry, M. A. (2024). Integrating automated drip irrigation and organic matter to improve enzymatic performance and yield of water efficient chilli in Karst Region. *Journal of Ecological Engineering*, *25*(11), 175–187. https://doi.org/10.12911/22998993/192820
6. Bashir, O., Ali, T., Baba, Z. A., Rather, G. H., Bangroo, S. A., Mukhtar, S. D., Naik, N., Mohiuddin, R., Bharati, V., Bhat, R. A. (2021). Soil Organic Matter and Its Impact on Soil Properties and Nutrient Status. In G. H. Dar, R. A. Bhat, M. A. Mehmood, K. R. Hakeem (Eds), *Microbiota and Biofertilizers, 2* (pp. 129–159). Springer International Publishing. https://doi.org/10.1007/978-3-030-61010-4_7
7. Bates, L. S., Waldren, R. P., Teare, I. D. (1973). Rapid determination of free proline for water-stress studies. *Plant and Soil*, *39*(1), 205–207. https://doi.org/10.1007/BF00018060
8. Boafo, D. K., Kraisornpornson, B., Panphon, S., Owusu, B. E., Amaniampong, P. N. (2020). Effect of organic soil amendments on soil quality in oil palm production. *Applied Soil Ecology*, *147*, 103358. https://doi.org/10.1016/j.apsoil.2019.09.008
9. Brant, A. N., Chen, H. Y. H. (2015). Patterns and mechanisms of nutrient resorption in plants. *Critical Reviews in Plant Sciences*, *34*(5), 471–486. https://doi.org/10.1080/07352689.2015.1078611
10. Cellier, A., Gauquelin, T., Baldy, V., Ballini, C. (2014). Effect of organic amendment on soil fertility and plant nutrients in a post-fire Mediterranean ecosystem. *Plant and Soil*, *376*(1–2), 211–228. https://doi.org/10.1007/s11104-013-1969-5
11. Chamizo-Ampudia, A., Sanz-Luque, E., Llamas, A., Galvan, A., Fernandez, E. (2017). Nitrate reductase regulates plant nitric oxide homeostasis. *Trends in Plant Science*, *22*(2), 163–174. https://doi.org/10.1016/j.tplants.2016.12.001
12. Comte, I., Colin, F., Grünberger, O., Follain, S., Whalen, J. K., Caliman, J.-P. (2013). Landscape-scale assessment of soil response to long-term organic and mineral fertilizer application in an industrial oil palm plantation, Indonesia. *Agriculture, Ecosystems & Environment*, *169*, 58–68. https://doi.org/10.1016/j.agee.2013.02.010
13. De Corato, U., Viola, E., Keswani, C., Minkina, T. (2024). Impact of the sustainable agricultural practices for governing soil health from the perspective of a rising agri-based circular bioeconomy. *Applied Soil Ecology*, *194*, 105199. https://doi.org/10.1016/j.apsoil.2023.105199
14. Elvitriana, Munir, E., Delvian, Wahyuningsih, H. (2021). Organic substances reduction in palm oil mill effluent (pome) after cultivation with locally isolated microalgae. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *80*(2), 98–105. https://doi.org/10.37934/arfmts.80.2.98105
15. Evans, H. J., Nason, A. (1953). Pyridine nucleotide-nitrate reductase from extracts of higher plants. *Plant Physiology*, *28*(2), 233–254. https://doi.org/10.1104/pp.28.2.233
16. Geisseler, D., Smith, R., Cahn, M., Muramoto, J. (2021). Nitrogen mineralization from organic fertilizers and composts: Literature survey and model fitting. *Journal of Environmental Quality*, *50*(6), 1325–1338. https://doi.org/10.1002/jeq2.20295
17. H, Okolie., E, Ekwuribe., C.C, Obasi., E.A, Obidiebube., S.N, Obasi. (2019). Evaluation of palm oil mill effluent (POME) Impact on soil chemical properties and weed cover in awka–rain forest zone of Nigeria. *Canadian Journal of Agriculture and Crops*, *4*(2), 93–100. https://doi.org/10.20448/803.4.2.93.100
18. Hadwan, M. H., Abed, H. N. (2016). Data supporting the spectrophotometric method for the estimation of catalase activity. *Data in Brief*, *6*, 194–199. https://doi.org/10.1016/j.dib.2015.12.012
19. Hasanuzzaman, M., Bhuyan, M. H. M., Zulfiqar, F., Raza, A., Mohsin, S., Mahmud, J., Fujita, M., Fotopoulos, V. (2020). Reactive oxygen species and antioxidant defense in plants under abiotic stress: revisiting the crucial role of a universal defense regulator. *Antioxidants*, *9*(8), 681. https://doi.org/10.3390/antiox9080681
20. Hau, L. J., Shamsuddin, R., May, A. K. A., Saenong, A., Lazim, A. M., Narasimha, M., Low, A. (2020). Mixed composting of palm oil empty fruit bunch (EFB) and palm oil mill effluent (POME) with various organics: An analysis on final macronutrient content and physical properties. *Waste and Biomass Valorization*, *11*(10), 5539–5548. https://doi.org/10.1007/s12649-020-00993-8
21. Imam, S. S., Sani, S., Mujahid, M., Adnan, R. (2025). Valuable resources recovery from palm oil mill effluent (POME): A short review on sustainable wealth reclamation. *Waste Management Bulletin*, *3*(1), 1–16. https://doi.org/10.1016/j.wmb.2024.12.002
22. Kabala, C., Jedrzejewski, S. (2024). Comparison of cation exchange capacity extraction methods for soil data harmonization and soil classification in Central

and East Europe. *Geoderma*, *450*, 117044. https://doi.org/10.1016/j.geoderma.2024.117044

23. Krishnan, Y., Bong, C. P. C., Azman, N. F., Zakaria, Z., Othman, N., Abdullah, N., Ho, C. S., Lee, C. T., Hansen, S. B., Hara, H. (2017). Co-composting of palm empty fruit bunch and palm oil mill effluent: Microbial diversity and potential mitigation of greenhouse gas emission. *Journal of Cleaner Production*, *146*, 94–100. https://doi.org/10.1016/j.jclepro.2016.08.118
24. Kumari, R., Bhatnagar, S., Deepali, Mehla, N., Vashistha, A. (2022). Potential of organic amendments (AM fungi, PGPR, Vermicompost and Seaweeds) in combating salt stress... A review. *Plant Stress*, *6*, 100111. https://doi.org/10.1016/j.stress.2022.100111
25. Li, Y., Feng, X., Huai, Y., Hassan, M. U., Cui, Z., Ning, P. (2024). Enhancing crop productivity and resilience by promoting soil organic carbon and moisture in wheat and maize rotation. *Agriculture, Ecosystems & Environment*, *368*, 109021. https://doi.org/10.1016/j.agee.2024.109021
26. Lisan, A. R. K., Amalia, D., Dewanti, T. O., Pratama, A. P., Putra, R. A., Yudhanto, K. D., Azzahra, H. S., & Wardani, N. A. (2025). Enhancing the sandy soil structure of the Samas coastal area using anaerobic digestion sludge derived from palm oil mill effluent. *Jurnal Tanah Dan Sumberdaya Lahan*, *12*(1), 97–106. https://doi.org/10.21776/ub.jtsl.2025.012.1.10
27. Liu, T., Wu, L., Tang, S., Shaaban, M., Meng, L., Xu, M., Zhang, W. (2025). Positive effects of amendments on crop yield and organic carbon in sandy soils are regulated by aridity: A global meta-analysis. *Geoderma*, *462*, 117540. https://doi.org/10.1016/j.geoderma.2025.117540
28. Loh, S. K., Lai, M. E., Ngatiman, M. (2019). Vegetative growth enhancement of organic fertilizer from anaerobically-treated palm oil mill effluent (POME) supplemented with chicken manure in food-energy-water nexus challenge. *Food and Bioproducts Processing*, *117*, 95–104. https://doi.org/10.1016/j.fbp.2019.06.016
29. Maehly, A. C. (1954). The Assay of Catalases and Peroxidases. In D. Glick (Ed.), *Methods of Biochemical Analysis* (1st edn, Vol. 1, pp. 357–424). Wiley. https://doi.org/10.1002/9780470110171.ch14
30. Maffia, A., Oliva, M., Marra, F., Mallamaci, C., Nardi, S., Muscolo, A. (2025). Humic substances: bridging ecology and agriculture for a greener future. *Agronomy*, *15*(2), 410. https://doi.org/10.3390/agronomy15020410
31. Murtaza, G., Hassan, N. E., Usman, M., Deng, G., Ahmed, Z., Iqbal, J., Elshikh, M. S., Rizwana, H., Ali, B., Iqbal, R., Lackner, M. (2025). Synergistic effects of allantoin and *Achyranthes japonica*-biochar profoundly alleviate lead toxicity during barley growth. *Ecotoxicology and Environmental Safety*, *290*, 117784. https://doi.org/10.1016/j.ecoenv.2025.117784
32. Mutar, Z. H., Al-Baldawi, I. A., Abdullah, S. R. S. (2025). Sustainable treatment of palm oil mill effluent and repurposing of sludge as a micronutrient resource. *Journal of King Saud University – Science*, *37*, 9862025. https://doi.org/10.25259/JKSUS_986_2025
33. Nadeem Shah, M., Wright, D. L., Hussain, S., Koutroubas, S. D., Seepaul, R., George, S., Ali, S., Naveed, M., Khan, M., Tanveer Altaf, M., Ghaffor, K., Dawar, K., Syed, A., Eswaramoorthy, R. (2023). Organic fertilizer sources improve the yield and quality attributes of maize (*Zea mays* L.) hybrids by improving soil properties and nutrient uptake under drought stress. *Journal of King Saud University - Science*, *35*(4), 102570. https://doi.org/10.1016/j.jksus.2023.102570
34. Ngone, M. A., Ajoacha, D. M.-B., Achiri, D. T., Tchakounté, G. V. T., Ruppel, S., Tening, A. S., Ngosong, C. (2023). Potential of bio-organic amendment of palm oil mill effluent manure and plant growth-promoting bacteria to enhance the yield and quality of maize grains in Cameroon. *Soil Security*, *11*, 100090. https://doi.org/10.1016/j.soisec.2023.100090
35. Nurlaeny, N., Arifin, M., Sobardini, D. (2017). Utilization of mill effluent for growth, availability and uptake of nutrients by palm oil seedlings. *Journal of Agricultural Science and Technology B*, *7*(5). https://doi.org/10.17265/2161-6264/2017.05.005
36. Ollivier, J., Flori, A., Cochard, B., Amblard, P., Turnbull, N., Syahputra, I., Suryana, E., Lubis, Z., Surya, E., Sihombing, E., Gasselin, D. T. (2017). Genetic variation in nutrient uptake and nutrient use efficiency of oil palm. *Journal of Plant Nutrition*, *40*(4), 558–573. https://doi.org/10.1080/01904167.2016.1262415
37. Rahman, N., Giller, K. E., De Neergaard, A., Magid, J., Van De Ven, G., Bruun, T. B. (2021). The effects of management practices on soil organic carbon stocks of oil palm plantations in Sumatra, Indonesia. *Journal of Environmental Management*, *278*, 111446. https://doi.org/10.1016/j.jenvman.2020.111446
38. Rawat, N., Singla-Pareek, S. L., Pareek, A. (2021). Membrane dynamics during individual and combined abiotic stresses in plants and tools to study the same. *Physiologia Plantarum*, *171*(4), 653–676. https://doi.org/10.1111/ppl.13217
39. Ray, R. L., Kularathna, K. M., Griffin, R. W., Abeysingha, N., Woldesenbet, S., Elhassan, A., Awal, R., Fares, A. (2025). Enhancing plant and soil health through organic amendments in a humid environment. *Rhizosphere*, *35*, 101126. https://doi.org/10.1016/j.rhisph.2025.101126

40. Razzaq, S., Zhou, B., Ullah, Z., Zia-ur-Rehman, M., Guo, H., Adil, M., Xiaopeng, C., Qian, L. W. (2024). Exploring the impact of organic and inorganic amendments, with foliar application of iron nanoparticles, on cadmium stabilization and growth of maize in wastewater irrigated-soil. *Journal of Hazardous Materials Letters*, *5*, 100111. https://doi.org/10.1016/j.hazl.2024.100111
41. Samaei, F., Emami, H., Lakzian, A. (2022). Assessing soil quality of pasture and agriculture land uses in Shandiz county, northwestern Iran. *Ecological Indicators*, *139*, 108974. https://doi.org/10.1016/j.ecolind.2022.108974
42. Sanches, J. P., Costa, S. S., Das Graças, D. A., Silva, A., Baião, G. C., Moreira, R. G., Magalhães, M. M., Cunha, R. L., Baraúna, R. A. (2024). Soil fertilization with palm oil mill effluent has a short-term effect on the bacterial diversity of an amazonian agricultural land area. *Microorganisms*, *12*(3), 507. https://doi.org/10.3390/microorganisms12030507
43. Schönbeck, L., Arteaga, M., Mirza, H., Coleman, M., Mitchell, D., Huang, X., Ortiz, H., Santiago, L. S. (2023). Plant physiological indicators for optimizing conservation outcomes. *Conservation Physiology*, *11*(1), coad073. https://doi.org/10.1093/conphys/coad073
44. Shahid, M. (2021). Effect of soil amendments on trace element-mediated oxidative stress in plants: Meta-analysis and mechanistic interpretations. *Journal of Hazardous Materials*, *407*, 124881. https://doi.org/10.1016/j.jhazmat.2020.124881
45. Sharma, N., Chaudhary, A., Sharma, N., Shukla, S., Joshi, N. C., Vishwakarma, K., Singh, P. K., Mishra, A. (2025). Plant Nutrient Requirements and Nutrient Homeostasis in Plants. In N. C. Joshi, T. Leustek, P. K. Singh (Eds), *Soil Health and Nutrition Management* (pp. 1–20). CABI. https://doi.org/10.1079/9781800624597.0001
46. Siddiquee, S., Shafawati, S. N., Naher, L. (2017). Effective composting of empty fruit bunches using potential Trichoderma strains. *Biotechnology Reports*, *13*, 1–7. https://doi.org/10.1016/j.btre.2016.11.001
47. Supriatna, J., Setiawati, M. R., Sudirja, R., Suherman, C., Bonneau, X. (2023). Migration from inorganic to organic fertilization for a more sustainable oil palm agro-industry. *Heliyon*, *9*(12), e22868. https://doi.org/10.1016/j.heliyon.2023.e22868
48. Suvendran, S., Acevedo, M. F., Smithers, B., Walker, S. J., Xu, P. (2025). Soil fertility and plant growth enhancement through compost treatments under varied irrigation conditions. *Agriculture*, *15*(7), 734. https://doi.org/10.3390/agriculture15070734
49. Tambe, E. B., Okonkwu, A. U., I.E., M.-N., C.O., C., E., A., S.C., O., I.N., E., U.F., E., J., O. (2024). Determinants of physicochemical composition of palm oil mill effluent—implications on environment and bio-digester treatment design. *Applied Environmental Research*. https://doi.org/10.35762/AER.2024058
50. 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). https://doi.org/10.57647/IJROWA-XQPD-6789
51. Van De Velde, E., Steppe, K., Van Labeke, M.-C. (2023). Leaf morphology, optical characteristics and phytochemical traits of butterhead lettuce affected by increasing the far-red photon flux. *Frontiers in Plant Science*, *14*, 1129335. https://doi.org/10.3389/fpls.2023.1129335
52. Wang, C., Kuzyakov, Y. (2024). Soil organic matter priming: The pH effects. *Global Change Biology*, *30*(6), e17349. https://doi.org/10.1111/gcb.17349
53. Xu, J., Li, Y., Li, L. (2025). A Comprehensive Review of the effects of organic amendments on soil health and fertility: mechanisms, greenhouse gas emissions, and implications for sustainable agriculture. *Agronomy*, *15*(12), 2705. https://doi.org/10.3390/agronomy15122705
54. Yang, M., Zhou, D., Hang, H., Chen, S., Liu, H., Su, J., Lv, H., Jia, H., Zhao, G. (2024). Effects of Balancing Exchangeable Cations Ca, Mg, and K on the Growth of Tomato Seedlings (*Solanum lycopersicum* L.) Based on increased soil cation exchange capacity. *Agronomy*, *14*(3), 629. https://doi.org/10.3390/agronomy14030629
55. Yusuf, F. R., Suprihatin, S., Indrasti, N. S. (2025). Improving the environmental performance of palm oil industry through the utilization of empty oil palm bunches as organic fertilizer and biochar for soil amendment. *Environmental Challenges*, *20*, 101185. https://doi.org/10.1016/j.envc.2025.101185
56. Zhao, Y., Chen, Y., Dai, H., Cui, J., Wang, L., Sui, P. (2021). Effects of organic amendments on the improvement of soil nutrients and crop yield in sandy soils during a 4-year field experiment in Huang-Huai-Hai Plain, Northern China. *Agronomy*, *11*(1), 157. https://doi.org/10.3390/agronomy11010157
57. Zulfiqar, F., Ashraf, M. (2023). Proline alleviates abiotic stress induced oxidative stress in plants. *Journal of Plant Growth Regulation*, *42*(8), 4629–4651. https://doi.org/10.1007/s00344-022-10839-3