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Pengaruh Bio Solid 17 Berbasis Pome Terhadap Ph, Kapasitas Tukar Kation, dan Kapasitas Menahan Air Tanah Inceptisol

Effects of Pome-Based Bio Solid 17 On Ph, Cation Exchange Capacity, and Water-Holding Capacity of Inceptisol

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ABSTRACT

Inceptisol is one of the most widely distributed soil types in tropical regions, including Indonesia, which is characterized by high rainfall and intensive weathering processes. These conditions result in strong nutrient leaching, low cation exchange capacity and moderately to low soil pH, thereby limiting nutrient availability, fertilizer efficiency, and crop productivity, particularly in oil palm (Elaeis guineensis) plantations. This study aimed to evaluate the effect of Bio Solid 17, an organic soil amendment derived from palm oil mill effluent sludge, on the chemical and physical properties of Inceptisol through a laboratory incubation experiment. The incubation was conducted for two months using a randomized complete block design design with five application rates of Bio Solid 17, namely 0, 5, 10, 15, and 20 kg ha^{-1}, each with five replications. The observed parameters included soil pH, cation exchange capacity, and water-holding capacity, which were analyzed using standard laboratory methods. The results showed that the application of Bio Solid 17 significantly improved the quality of Inceptisol in a dose-dependent manner. Soil pH increased from strongly acidic conditions (4.85) in the control treatment to near neutral (6.19) at the highest application rate. Soil cation exchange capacity also increased significantly from 34.41 to 47.49 cmolc kg^{-1}, indicating enhanced soil capacity to adsorb and retain nutrients. In addition, soil water-holding capacity increased from 46.82% to 55.81%, reflecting improved soil aggregation and moisture retention. Overall, Bio Solid 17 has strong potential as a sustainable organic soil amendment to improve the chemical and physical fertility of Inceptisol. The utilization of solid materials supports circular economy principles by converting agro-industrial waste into value-added agricultural inputs.

Keywords: organic; sludge; soil chemical; soil physical; Inceptisol.

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INTRODUCTION

Inceptisols occupy a substantial proportion of agricultural land in tropical regions, particularly in Indonesia, where intense rainfall and continuous weathering accelerate soil formation yet simultaneously promote severe nutrient losses.Indonesia's humid tropical climate with relative humidity around 90% and annual rainfall exceeding 2000 mm facilitates the rapid leaching of base cations such as Ca^{2+}, Mg^{2+}, and K^{+}, leading to strongly acidic soil conditions (pH < 5.5). Such acidification decreases nutrient availability, increases Al^{3+} toxicity, and ultimately diminishes the chemical fertility of these soils(Shetty et al., 2021). A key limitation of Inceptisols is their dominance of low-activity 1:1 clay minerals, especially kaolinite, which have low permanent charge and consequently low cation exchange capacity (CEC). Soils with low CEC are prone to nutrient leaching, reducing fertilizer use efficiency and increasing environmental nutrient losses(Ciric et al., 2023). This constraint is further intensified by typically low organic matter content (<2%), which plays a foundational role in soil structure formation, biological activity, and the development of reactive functional groups responsible for variable charge and nutrient adsorption.

Improving the chemical and physical properties of Inceptisols is therefore critical for sustaining agricultural productivity, particularly in oil palm (*Elaeis guineensis*) plantations that dominate Indonesia's land-use systems. The oil palm sector has expanded rapidly, with plantation area increasing by 144% from 5.78 million ha in 2010 to 14.17 million ha in 2023 (Martalita et al., 2025). This expansion intensifies pressure on soil resources and underscores the need for soil management practices that enhance resilience, nutrient-use efficiency, and long-term sustainability. One promising strategy involves utilizing organic soil conditioners derived from agro-industrial byproducts. Among these, palm oil mill effluent (POME) represents a high-organic-load waste produced in large volumes during oil palm processing. Untreated POME poses environmental challenges due to its high BOD and COD, yet properly treated POME sludge contains abundant organic matter, humic substances, beneficial microbes, and essential macro- and micronutrients (Imam et al., 2025). Converting POME into solid organic amendments supports circular economy principles and offers an environmentally responsible approach to improving soil quality.

Bio Solid 17, an organic soil conditioner derived from biologically treated POME sludge, has shown potential to enhance soil biological activity, nutrient availability, and soil structure. However, scientific evidence regarding its mechanisms and optimal application rates particularly for improving key Inceptisol properties remains limited. Furthermore, controlled incubation studies that isolate its effects on fundamental soil indicators such as pH, CEC, and water-holding capacity (WHC) are lacking. Addressing this knowledge gap is crucial for optimizing the use of POME-based amendments in tropical agriculture.

Therefore, this study aims to evaluate the effects of multiple application rates of Bio Solid 17 on the chemical and physical properties of Inceptisol under controlled incubation conditions. We hypothesize that Bio Solid 17 will significantly increase soil pH, CEC, and WHC through combined mechanisms of organic matter addition, base cation enrichment, and structural improvement. The findings are expected to advance scientific understanding of soil amendment function and contribute practical recommendations for sustainable soil fertility management in tropical agricultural systems.

METHOD

Soil Sampling and Preparation. The soil used in this study was classified as Inceptisol, collected from the topsoil layer (0–20 cm) of an agricultural field in Jatinangor, West Java, Indonesia and the research was conducted from October to December 2025. The soil was air-dried for 5 days, gently crushed, and sieved through a 2-mm mesh to remove gravel and plant residues. Subsamples were analyzed prior to incubation to determine initial soil properties, including texture, pH, organic carbon, total nitrogen, exchangeable cations, and CEC, following standardized methods (Soil Survey Staff, 2014). Bio Solid 17 was produced from palm oil mill effluent (POME) sludge subjected to a chemical coagulation–flocculation treatment from BGA Ltd.

Experimental Design and Treatments. A two-month incubation experiment (8 weeks) was conducted under controlled laboratory conditions (temperature 27 ± 2 °C; relative humidity 70–80%). The

experiment followed a Randomized Complete Block Design (RCBD) with five treatments and five replications (n = 25) The treatments consisted of five application rates of Bio Solid 17:
A = Control (0 kg ha^{-1})
B = 0.5× recommended dose (5 kg ha^{-1})
C = 1.0× recommended dose (10 kg ha^{-1})
D = 1.5× recommended dose (15 kg ha^{-1})
E = 2.0× recommended dose (20 kg ha^{-1})

One kilogram of sieved soil was placed in plastic incubation jars (2 L capacity). Bio Solid 17 was thoroughly mixed into each soil sample based on treatment rates. Soil moisture was maintained at 60% of water-holding capacity throughout incubation by weighing jars every 48 hours and adding distilled water as needed.

Laboratory Analytical Methods. Soil pH was measured in a 1:2.5 soil to water suspension. Samples were mechanically shaken for 30 minutes before measurement using a calibrated glass-electrode pH meter.

Cation Exchange Capacity (CEC). CEC was determined using the ammonium acetate (NH_4OAc) 1 N method at pH 7.0 The procedure involved: Saturation of exchange sites with ammonium ions, Removal of excess NH_4^+, Displacement using 1 N KCl,Quantification of NH_4^+ using steam distillation. Results were expressed in cmolc kg^{-1}.

Water-Holding Capacity (WHC). WHC was determined gravimetrically. Soil samples were: Saturated for 24 hours, Allowed to drain for 2 hours on a tension table, Oven-dried at 105 °C for 24 hours.

WHC (%) = ((Water-saturated weight − Oven-dry weight) / Oven-dry weight) × 100.
All measurements were conducted in triplicate per sample for quality assurance.

Data Analyze. Data were processed and analyzed using RStudio software. Violin plots were generated to visualize the distribution and variability of parameter dose Bio Solid 17 application rates, with embedded boxplots indicating median and interquartile ranges.

RESULT & DISCUSSION

Soil pH. Soil pH is a fundamental indicator of soil chemical reactions and nutrient availability, and in this study it served as a basis for understanding how suspended solid application influences soil acidity dynamics in young oil palm plantations.

Pict 1 shows a clear improvement in soil pH following the application of Bio Solid 17, with values increasing from strongly acidic conditions (pH 4.85 in the control) to near-optimal levels at the highest application rate (pH 6.19). Such improvement is fundamental for enhancing nutrient availability and supporting healthier root development in oil palm plantations. Oil palm grows best in slightly acidic to neutral soils (pH 5.0–6.5), where nutrient solubility is balanced and the risk of toxicity is minimal. In contrast, many Indonesian Inceptisols exhibit pH < 5 due to high rainfall–induced leaching of base cations and repeated use of ammonium based fertilizers(Dubos et al., 2017). These acidic conditions intensify phosphorus fixation by Fe and Al oxides, thereby reducing the availability of plant-accessible phosphate ions and limiting early frond development, root branching, and the formation of female inflorescences (X. Chen et al., 2022).

The data in Pict 1 further indicate that soil pH begins to shift significantly from the 1.0× rate onward (pH 5.40), suggesting that Bio Solid 17 supplies sufficient base-forming cations and organic functional groups to neutralize exchangeable acidity. Low pH also reduces the availability of exchangeable Ca and Mg two essential cations for structural stability, enzymatic activation, and chlorophyll formation while simultaneously increasing the solubility of toxic Al^{3+} ions (Miyazawa et al., 2001). Aluminum toxicity, a common constraint in highly weathered tropical soils, disrupts root cell division and inhibits both root elongation and lateral root formation, resulting in shallow and inefficient root systems (Ofoe et al., 2023).

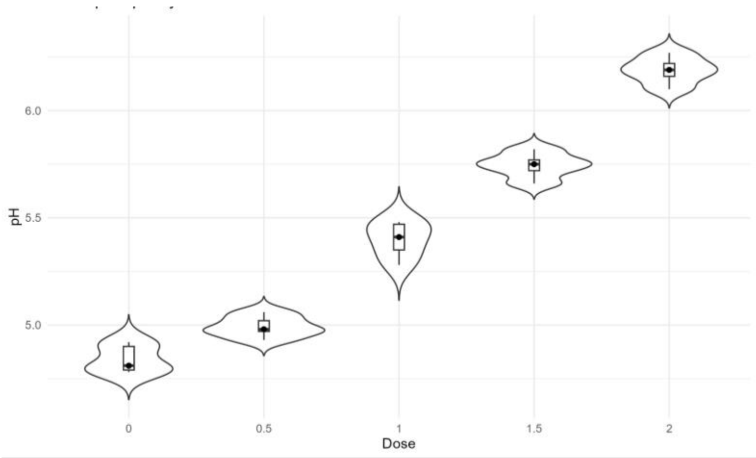

Figure 1. Violin Plot Soil pH After Treatment

The substantial rise in pH at the 1.5× (pH 5.75) and 2.0× (pH 6.19) rates demonstrates the capacity of Bio Solid 17 to alleviate acidity-induced limitations. By reducing exchangeable Al^{3+} and increasing base saturation, the amendment improves the chemical environment of the rhizosphere, thereby restoring the availability of P, Ca, and Mg. This shift toward the optimal pH range enhances root proliferation within the top 0–30 cm soil layer, where most fine absorbing roots of oil palm are concentrated. A more extensive root system enables better exploration of soil volume, resulting in improved uptake of N, P, K, and Mg nutrients crucial for frond formation andflowering (Arslan et al., 2026).

Enhanced soil pH also improves fertilizer use efficiency by reducing nutrient fixation and leaching, especially for mobile cations such as K^+ and Mg^{2+}(D. Chen et al., 2022). Thus, the synergistic improvement in soil chemistry and root physiology contributes not only to higher productivity but also to more sustainable nutrient management. Overall, the pH enhancement observed in Pict 1 forms the basis for improved nutrient availability, healthier root architecture, and enhanced growth performance of oil palm on acidic Inceptisols.

Soil CEC. Cation Exchange Capacity (CEC) reflects the soil's ability to retain and exchange nutrient cations, and its significant increase following suspended solid application highlights the amendment's effectiveness in enhancing soil fertility status.

Pict 2 shows a progressive and statistically significant increase in soil CEC with higher application rates of Bio Solid 17, rising from 34.41 cmol kg^{-1} in the control to 47.49 cmol kg^{-1} at the 2.0× rate. The transition from "a" to "c" groupings indicates clear improvement beginning at the 1.0× rate and becoming highly significant at 1.5× and 2.0× applications. Because oil palm is a nutrient demanding perennial crop requiring continuous supplies of N, P, K, Mg, and key micronutrients, improvements in CEC directly influence long-term soil fertility and fertilizer-use efficiency(Ketterings et al., 2002).

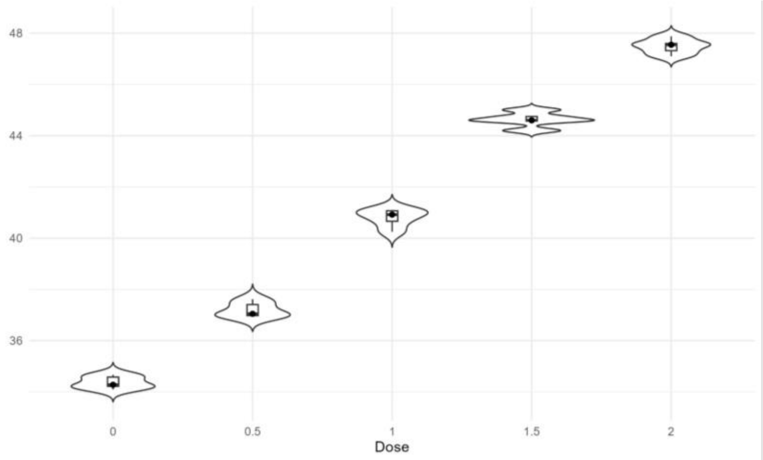

Figure 2. Violin Plot Soil CEC

In tropical Inceptisols, nutrient loss through leaching is a major constraint due to low inherent CEC and high rainfall. This is particularly critical for potassium and magnesium two highly mobile cations essential for osmotic regulation, chlorophyll formation, and oil biosynthesis in oil palm. The increase in CEC observed in Pict 2 reflects the contribution of Bio Solid 17's stabilized organic matter, which provides carboxyl, hydroxyl, and phenolic functional groups that expand the soil's exchange sites(Jiang et al., 2018). These additional negatively charged surfaces bind nutrient cations more effectively, reducing downward leaching and keeping fertilizers within the plant's rooting zone. As CEC increases, nutrient retention becomes better synchronized with the seasonal physiological demands of oil palm, such as rapid frond expansion and fresh fruit bunch (FFB) development (Suwardi et al., 2020). This stabilization of the nutrient pool allows for more consistent root uptake and improves the plant's ability to maintain optimal tissue nutrient concentrations, ultimately enhancing both vegetative growth and reproductive performance.

From a management standpoint, higher CEC offers measurable economic and environmental advantages. With reduced nutrient losses, plantations can lower fertilizer application rates without compromising productivity an important benefit considering fertilizer expenses account for 30–45% of total operational costs (Arifin et al., 2022). Furthermore, reduced leaching mitigates nutrient contamination in waterways, supporting RSPO and ISPO sustainability criteria (Nabila et al., 2023). Overall, the substantial increase in CEC observed with Bio Solid 17 application strengthens soil nutrient retention and contributes to more efficient, cost-effective, and environmentally responsible nutrient management in oil palm plantations.

Pict 3 shows a clear and consistent increase in soil water-holding capacity (WHC) following the application of Bio Solid 17, rising from 46.82% in the control to 55.81% at the 2.0× rate. The statistical grouping (a–c) indicates that even the 0.5× rate significantly improves WHC compared with the control, while the highest two application rates provide the greatest enhancement. Because oil palm requires a continuous water supply of 1,200–1,700 mm per year, any improvement in WHC has direct implications for maintaining physiological stability, particularly under fluctuating rainfall patterns common in tropical regions(Afandi et al., 2022).

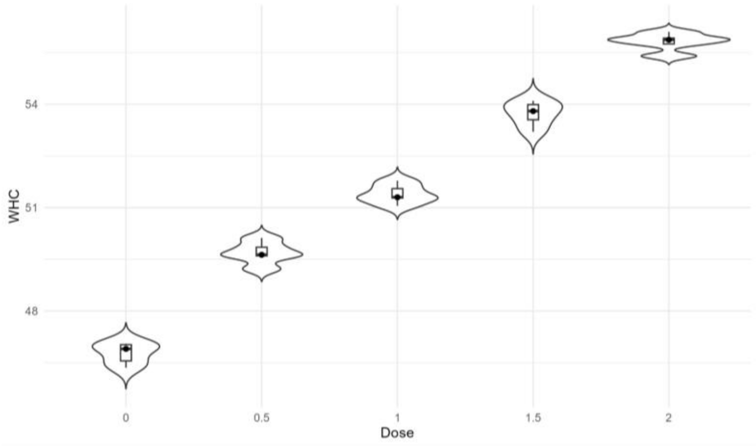

Figure 3. Violin Plot Soil WHC

Enhanced WHC Supports. Low WHC limits the soil's ability to retain moisture between rainfall events, leading to short-term water deficits that reduce stomatal conductance, impair carbon assimilation, and restrict nutrient uptake(Bañón et al., 2022). These moisture constraints are especially detrimental during critical growth phases such as frond expansion, inflorescence differentiation, and fresh fruit bunch (FFB) formation(Agusta et al., 2020). The WHC increases seen in Pict 3 reflect the role of Bio Solid 17's organic matter in improving soil aggregation and increasing micropore volume, creating a more structured pore network capable of storing plant-available water while maintaining adequate aeration. As WHC improves, the soil remains moist over longer intervals, allowing palms to sustain optimal stomatal behavior and photosynthetic activity (Ahmed et al., 2023). Consistent soil moisture supports stable flower primordia development and reduces fluctuations in fruit bunch production that commonly occur during short dry spells (Hajiboland & Farhanghi, 2011). This enhanced moisture retention becomes even more critical during climate anomalies such as El Niño, when extended dry periods can severely limit soil water availability. Soils amended with higher rates of Bio Solid 17 (1.5× and 2.0×) demonstrate greater resilience, buffering palms against moisture stress and reducing the risk of long-term yield decline. Overall, the stepwise increase in WHC demonstrated in Pict 3 highlights the effectiveness of Bio Solid 17 in strengthening soil physical properties, improving water retention, and supporting more stable oil palm productivity under both normal and climate-stressed conditions.

CONCLUSION

This study demonstrates that the application of Bio Solid 17, an organic amendment derived from biologically treated POME sludge, significantly improves key chemical and physical properties of Inceptisol by increasing soil pH from strongly acidic conditions toward the optimal range for oil palm cultivation, reducing exchangeable acidity, enhancing nutrient availability and cation exchange capacity (CEC), and improving water-holding capacity (WHC), which reflects better soil aggregation and moisture storage, thereby collectively strengthening soil fertility and resilience; these results highlight the potential of Bio Solid 17 as a sustainable soil conditioner that supports long-term plantation productivity while aligning with circular-economy principles through the conversion of agro-industrial waste into a valuable agricultural input, although further field-scale validation is recommended to optimize dosage and assess long-term effects under varying climatic and management conditions.

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