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Optimization of Empty Fruit Bunch Application to Improve Soil Organic Carbon, Total Soil Nitrogen, Earthworm Populations, and Oil Palm Performance on Spodosols

Adhy Ardiyanto*, Suria Darma Tarigan, Rahayu Widyastuti, Budi Nugroho and Fathan Aldi Rivai

Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University, Bogor, Indonesia

**Corresponding author:* 1981adhy@apps.ipb.ac.id

Abstract

Using oil palm empty fruit bunches (EFB) as an organic amendment is a crucial strategy to improve soil quality in oil palm plantations, particularly on nutrient-poor Spodosol soils. This study aimed to evaluate the effects of 2 EFB application methods (incorporation into the soil and surface mulching) on soil organic carbon (SOC), nitrogen content, earthworm populations as soil biological indicators of fertility, and oil palm performance. A 12-month field experiment was conducted with observations every 4 months, using a completely randomized design (CRD) with 3 treatments and 9 replications each (n = 27 experimental units). The treatments included no EFB application (T0), EFB incorporated into the soil (T1), and EFB applied as surface mulch (T2). The results showed that both EFB application methods significantly increased SOC compared to the control, with the highest SOC observed in T2 (2.30±0.34%) after 12 months. Earthworm populations also increased progressively, reaching 19.33 individuals m^{-2} in T2. Pearson correlation analysis revealed a strong positive relationship between SOC content and earthworm abundance ($r = 0.60$; $p < 0.001$). These results confirm that EFB application, especially through surface mulching, is an effective and sustainable approach to enhancing soil quality, biological activity, and ecosystem functioning on Spodosols in oil palm plantations.

Keywords: EFB mulching; organic amendment; *Pontoscolex corethrurus*; soil biological indicators; Spodosols

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INTRODUCTION

Oil palm is one of the leading plantation commodities in Indonesia, with strong competitiveness and a promising future as a sustainable industry. According to data from Statistics Indonesia (2025), the area of oil palm plantations increased by 203.07% between 2003 and 2024. Oil palm plantations contribute to job creation and regional economic growth (Syahza and Asmit, 2019). Over recent decades, oil palm expansion has increasingly extended into marginal lands, including Spodosols that are widely distributed across Borneo Island. Spodosols are characterized by a spodic horizon formed through podzolization, involving the accumulation of organic matter complexed with aluminum and iron in subsurface layers. They typically occur in coarse-textured, quartz-rich soils with low organic matter content (Huang et al., 2022).

Intensive eluviation–illuviation processes in sandy parent materials create a pronounced contrast between the eluvial and spodic horizons, as reported in several recent studies (Ferro-Vázquez et al., 2020; Souza Junior et al., 2023; Fedenko et al., 2024; Kuligiewicz et al., 2024; Petticord et al., 2025). The characteristics of

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Spodosols promote high nutrient leaching and limited macronutrient availability, resulting in low oil palm productivity without appropriate nutrient management, as inorganic fertilizer efficiency in sandy soils is constrained by rapid leaching losses (Abdelfattah et al., 2021). Therefore, integrated nutrient management approaches combining organic and inorganic inputs are more relevant (Wang et al., 2024).

The rapid growth of the oil palm industry has also generated large amounts of biomass waste, particularly oil palm empty fruit bunches (EFB), which are expected to continue increasing as palm oil production rises (Januari et al., 2020). EFB is the main residue from fresh fruit bunch (FFB) processing and accounts for approximately 23% of the total harvested biomass, with high lignocellulosic and organic matter content (Sari et al., 2018). Despite its slow decomposition, EFB supplies carbon and nutrients for gradual-release soil amendment (Supriatna et al., 2022; Blankson et al., 2025), yet it remains underutilized and is often stockpiled or burned, contributing to greenhouse gas emissions and air pollution (Batcha et al., 2020).

Intensive oil palm management, involving frequent weeding and biomass removal without adequate residue return, can accelerate soil organic matter decomposition, leading to long-term carbon loss (Ashton-Butt et al., 2018; Formaglio et al., 2020; Rahman et al., 2021). Declines in SOC negatively affect soil structure, water retention, and soil biodiversity, ultimately increasing the risk of land degradation (Ashton-Butt et al., 2019; Kaupper et al., 2020). SOC is a key indicator of soil quality and fertility, contributing to aggregate formation, water storage, and energy supply for soil organisms (Guo et al., 2025; Santos et al., 2025).

Higher SOC content supports the development of more stable microhabitats for soil fauna, including earthworms, which are recognized as ecosystem engineers (Ahmed and Al-Mutairi, 2022). Earthworms enhance soil porosity and nutrient cycling through bioturbation activities and the production of nutrient-rich casts (Hallam et al., 2020; Capowiez et al., 2021; Traoré et al., 2022; Amadou et al., 2025). The addition of organic materials has been shown to increase earthworm populations by providing food resources and improving soil habitat conditions (Panta et al., 2026).

The use of EFB has been widely studied for various purposes, including bioenergy production and industrial materials (Mahardika et al., 2024; Utomo et al., 2024; Chitraningrum et al., 2025; Rosa Silva et al., 2026). In situ EFB application in oil palm plantations offers strategic advantages by reducing transport costs and carbon emissions while returning organic matter to the system. Several studies have examined the relationship between EFB application and earthworm populations, but most of these investigations were conducted outside the context of Spodosols, leaving a limited understanding of their interactions in sandy marginal soils (Tarigan et al., 2019; Hau et al., 2020; Lew et al., 2020; Edyson et al., 2022).

Organic matter application is a key soil management practice that increases SOC, improves soil physical and chemical properties, and supports biological activity, all of which are critical for agricultural productivity (Chiodi et al., 2025; Xu et al., 2025). The effectiveness of organic amendments depends on the application method, as soil incorporation and surface mulching produce distinct decomposition, carbon, and nitrogen dynamics (Readyhough et al., 2021; Abbas et al., 2024; Matisic et al., 2024). Soil health is fundamentally influenced by biological components, as biological activity drives improvements in soil physical and chemical properties (Zhelezova et al., 2025). Soil fauna play an important role in organic matter decomposition and nutrient cycling, making them reliable indicators of soil quality (Zhang et al., 2023; Mamabolo et al., 2024).

Earthworm populations serve as biological indicators of soil responses to EFB application, enhancing decomposition and nitrogen availability, which are essential for oil palm growth (Yadegari et al., 2020; Arifin et al., 2022; De la Peña et al., 2023). Nitrogen derived from EFB, which has a relatively high C/N ratio, does not necessarily increase soil nitrogen levels because some may be immobilized by microbes or be rapidly taken up by plants (Hu and Zhu, 2025; van Rijssel et al., 2025). Therefore, evaluating the effectiveness of EFB application requires consideration of both soil and plant nitrogen status, as represented by leaf nitrogen content.

Existing studies on oil palm EFB management have generally focused on short-term nutrient dynamics and yield responses, with limited attention to comparative effects of application methods on biological soil indicators and long-term SOC dynamics, particularly in Spodosols. Interactions among EFB application methods, SOC, earthworm populations, and soil and plant nitrogen status under field conditions remain

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insufficiently documented. Accordingly, the novelty of this study lies in its field-based comparative approach that integrates chemical, biological, and plant-based indicators to evaluate the effectiveness of different EFB application methods on Spodosols. Based on these considerations, this study aims to analyze changes in SOC following EFB application through soil incorporation and surface mulching, evaluate earthworm population responses, and assess their effects on soil nitrogen, leaf nitrogen content, and oil palm productivity.

MATERIALS AND METHOD

Research location and time

The study was conducted in a PT. Bumitama Gunajaya Agro (BGA) oil palm plantation on Spodosol soil in Kotawaringin Timur Regency (112°07’29” to 113°14’22” E and 1°11’50” to 3°18’51” S), Central Kalimantan, Indonesia (Borneo Island). The field experiment lasted for 12 months, from August 2023 to August 2024. Soil sampling and earthworm population observations were conducted every 4 months to monitor temporal changes. Soil sample analyses were conducted at the PT. BGA analytical laboratory.

Materials and equipment

The main material used in this study was EFB obtained from palm oil mill waste near the research site. Spodosol soil was used as the natural growing medium, while oil palm plants (*Elaeis guineensis* Jacq.) in the production phase (planted in 2011) served as the research objects. The tools used included a mini excavator (PC 50), soil sample rings, a soil auger, a sharp field knife, a hoe, and a measuring ruler. Soil fauna were identified using hand-sorting monoliths (50 cm × 50 cm × 20 cm), and organic carbon was analyzed using the Walkley and Black method.

Experimental design

The experiment was arranged in a completely randomized design (CRD) with 3 treatments and 9 replications, yielding 27 experimental plots. Each plot consisted of approximately 25 oil palm trees, which were treated as subsampling units. The treatments included: T0 = a control without EFB application; T1 = the application of 200 kg EFB per tree incorporated into the soil on both sides of the plant within a 2 m radius from the trunk; and T2 = the application of 200 kg EFB per tree applied as surface mulch within a 2 m radius from the trunk. Soil samples were collected at 2 depths (0 to 20 cm and 20 to 40 cm) and at 2 sampling locations: point X, corresponding to the EFB application area, and point Y, located 50 cm from point X toward the oil palm trunk. The different locations of points X and Y are illustrated in Figure 1.

Soil sampling and SOC analysis

SOC property sampling was conducted in August 2023 (before treatment) and every 4 months (December 2023, April 2024, and August 2024). Soil samples were collected from a depth of 0 to 20 cm at points X and Y to determine SOC, then composited and homogenized for analysis of earthworm populations and soil nitrogen. SOC content was determined using the Walkley and Black method (Nelson and Sommers, 1982). This method involves oxidizing organic matter

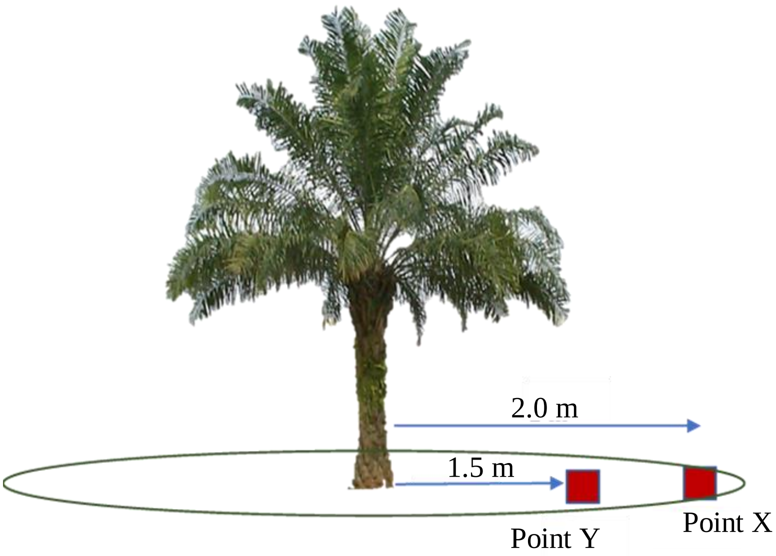

Figure 1. Location of soil sampling points

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with potassium dichromate ($K_2Cr_2O_7$) under acidic conditions, followed by titration with ferrous sulfate ($FeSO_4$). The results were used to evaluate the impact of EFB application on SOC content. Total soil nitrogen was determined using the Kjeldahl method, in which finely ground soil samples were digested with concentrated H_2SO_4 and a catalyst mixture, followed by distillation and titration to quantify total nitrogen content.

Earthworm population calculation

Earthworm populations were observed concurrently with soil sampling in each experimental unit. Earthworms were collected using the hand-sorting method on a soil monolith measuring 50 cm × 50 cm × 20 cm, which represented the EFB application zone. All earthworm individuals found were manually separated from the soil, then counted and expressed as the number of individuals per square meter (individuals m^{-2}) as a biological indicator of soil quality. The use of the hand-sorting method followed the recommendation of Nadolny et al. (2020), which is commonly used in soil ecology studies to obtain accurate field estimates of earthworm populations.

Leaf sampling

Leaf nitrogen concentration was determined using the Kjeldahl method following the procedure described by Kamireddy et al. (2023). Fully expanded leaf samples (fronds 17) from 13-year-old oil palm trees were collected in August 2023 and subsequently at 4-month intervals for up to 12 months. The samples were oven-dried at 65 °C to constant weight, finely ground, digested with concentrated H_2SO_4, and distilled to determine total nitrogen content.

Measurement of oil palm productivity

Oil palm productivity was assessed based on FFB yield data collected over a 6-month harvest period (September 2024 to February 2025), commencing 1 year after treatment application. FFB were harvested at 7 to 8-day intervals from 27 observation plots (9 palms per plot), and the yield data were subsequently converted to tons per hectare per 6-month period.

Data analysis

Data on SOC content, earthworm populations, soil nitrogen content, and leaf nitrogen content were analyzed using analysis of variance (ANOVA) according to the applied experimental design. ANOVA is a statistical method used to test whether there are significant differences among treatment means for the observed variables (Chicco et al., 2025). When a significant effect was detected at the 5% confidence level, Tukey's honestly significant difference (HSD) post hoc test was applied to determine which treatment pairs differed significantly. The correlation between SOC content and earthworm populations was analyzed using Pearson's correlation. Pearson's correlation is a parametric statistical analysis used to measure the strength and direction of a linear relationship between 2 quantitative variables (Tianle et al., 2026).

RESULTS AND DISCUSSION

Effect of EFB application on SOC

SOC content increased clearly in the EFB treatments, especially under surface mulching, while SOC in the control treatment tended to remain stable or decrease (Figure 2). At the 0 to 20 cm soil depth, SOC increased by 0.54% with surface application and by 0.48% with incorporated application, showing the effectiveness of EFB as a carbon source. Incorporation of EFB into the soil also increased SOC, but the increase was slightly lower due to more humid conditions (Tao et al., 2018). At depths of 20 to 40 cm, the increase was smaller because dissolved organic matter movement was limited by the characteristics of Spodosols. However, the moderate increase in the EFB treatments still indicates the contribution of dissolved organic matter to subsoil carbon. Noirot et al. (2022) reported that applying EFB in oil palm plantations increases SOC content compared to no treatment, mainly due to its role as a mulch in maintaining soil moisture and temperature, which supports decomposer activity. Rosenani et al. (2016) also stated that EFB decomposition occurs gradually and contributes to the addition of organic matter within 12 to 18 months after application.

The faster increase of SOC in T2 indicates the contribution of more easily decomposed organic matter fractions, while T1 shows slower but more stable carbon accumulation. This is consistent with Basile-Doelsch et al. (2020), who explained that organic carbon from fresh residues undergoes gradual humification and forms more protected organo-mineral associations in deeper layers. The incorporation of EFB by burying can increase SOC content (Nyasapoh et al., 2026); however, other studies have confirmed that surface application still produces the highest SOC due to better retention of biological activity (Adu et al., 2022).

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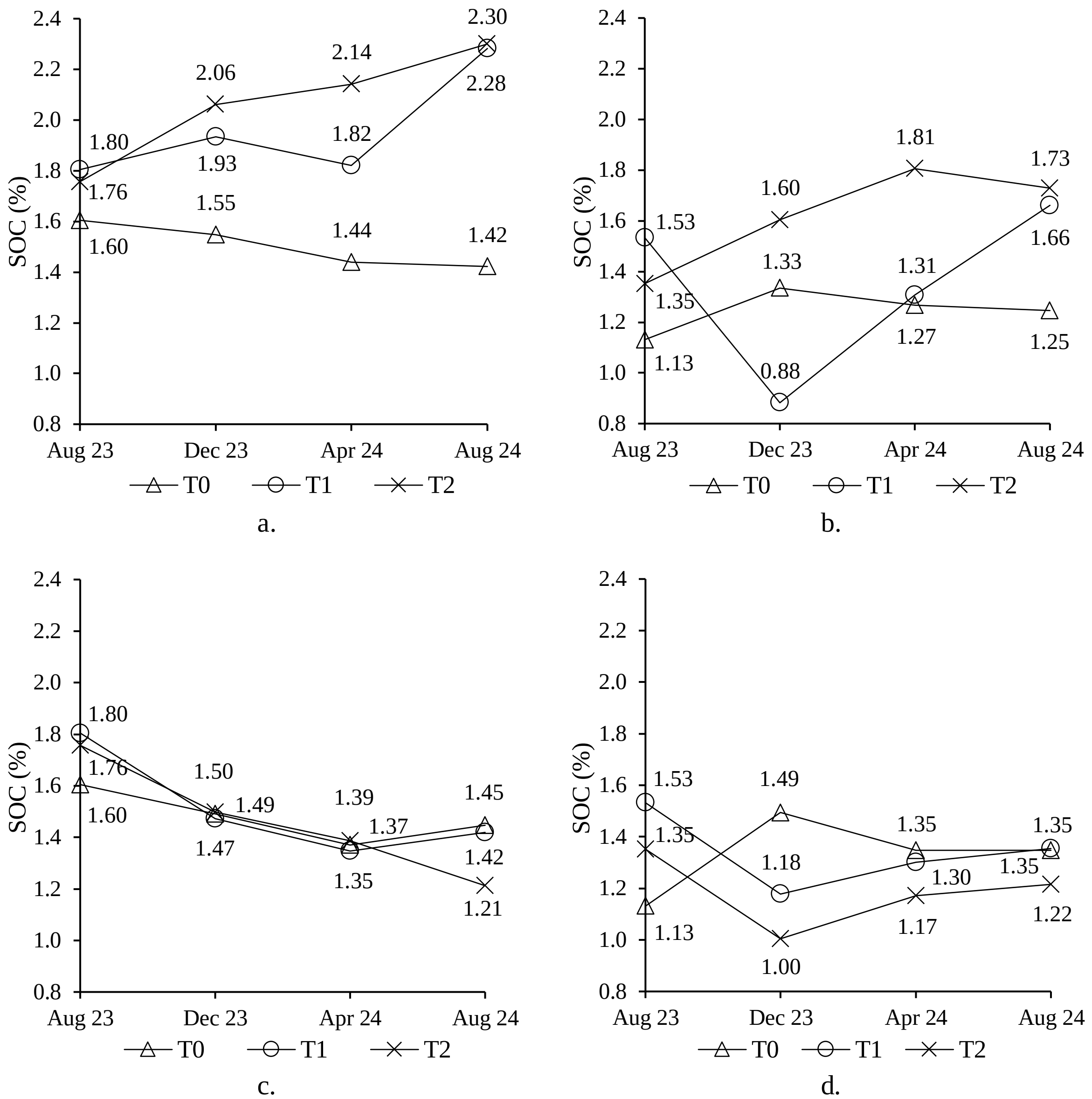

Figure 2. Dynamics of SOC under EFB treatments at different soil depths and observation locations: a) Point X (0–20 cm); b) Point X (20–40 cm); c) Point Y (0–20 cm); and d) Point Y (20–40 cm)

In terms of location, SOC values from August 2023 to August 2024 showed that site X (the EFB application spot) consistently had higher SOC than site Y, located 50 cm from the application point. This indicates that the improvement in soil organic matter from EFB is highly localized around the application zone. EFB has coarse particles and decomposes slowly, so lateral carbon movement is limited within 1 year (Shumba et al., 2024). These findings align with Rosenani et al. (2016), who reported that carbon accumulation remains concentrated in the organic residue application point. Therefore, the EFB application strategy should consider spacing and distribution patterns to ensure soil organic matter improvement across a wider plantation area.

SOC at 0 to 20 cm was higher than that at 20 to 40 cm for all treatments. This pattern reflects the concentration of organic inputs in the surface soil, where residue decomposition and microbial processes are generally more intense (Brindis-Santos et al., 2021; Wang et al., 2025). However, SOC increase at 20 to 40 cm was still observed at site X, indicating the contribution of dissolved organic carbon moving downward through water percolation and bioturbation (Rizinjirabake et al., 2019). The increase in deeper layers occurred more slowly because organic matter movement takes more time and is influenced by carbon stabilization processes through interactions with soil minerals such as Al and Fe oxides (Basile-Doelsch et al., 2020; Burgeon et al., 2021). These

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mechanisms are associated with the formation of organo-mineral complexes, which contribute to long-term carbon storage but only when there is a continuous supply of organic matter (Shabtai et al., 2024). Thus, repeated and long-term EFB application has the potential to increase carbon stocks not only in the topsoil but also in deeper layers through gradual humification, vertical carbon transport, and mineral stabilization.

Although incorporation of EFB into the soil (T1) increases contact between organic matter and the soil matrix and stimulates microbial activity for faster decomposition, this study showed that surface application (T2) tended to produce slightly higher SOC in the upper soil layer. This effect is related to mulching, which maintains soil moisture, reduces temperature fluctuations, and slows carbon mineralization, resulting in more stable carbon accumulation (Khoramizadeh et al., 2021; Rudolf et al., 2021). These findings show that surface mulching is more effective for long-term SOC enhancement than incorporation.

The decrease in SOC observed in treatment T1 at 20 to 40 cm depth in December 2023 (0.88±0.39%) was influenced by the positive soil priming effect, where the addition of fresh organic matter stimulates microbial activity and accelerates the decomposition of older, more resistant soil carbon (Mazzilli et al., 2014; Bernard et al., 2022). This mechanism may temporarily reduce carbon stock due to oxidation of older carbon to CO_2, before the balance is restored through humification and stabilization of newly added carbon associated with soil minerals (Fang et al., 2023; Martial et al., 2023). Therefore, the EFB application may temporarily accelerate the decomposition of old carbon before stabilization occurs.

Temporally, SOC dynamics showed the decomposition phases of EFB biomass. The increase from August to December 2023 reflected the rapid use of easily decomposed fractions as microbial energy sources. From December 2023 to April 2024, SOC tended to stagnate or decrease because the easily decomposed fractions were depleted, shifting decomposition to more resistant lignocellulose components. The minor fluctuation from April to August 2024 reflects the gradual breakdown of lignin and cellulose as the dominant components of EFB, which slows the decomposition rate but contributes to long-term stable carbon formation.

Effect of EFB application on total nitrogen in soil and oil palm leaves

Total soil nitrogen is one of the important indicators of soil fertility because it reflects the long-term nitrogen reserves stored in soil organic matter. In Spodosols, which generally have relatively low nutrient content and are dominated by stable organic matter, nitrogen dynamics are strongly influenced by organic matter inputs. The results of this study show that total soil nitrogen content was affected by oil palm EFB treatments and observation time, indicating the occurrence of nitrogen transformation processes in the soil (Table 1). At the initial observation (August 2023), soil nitrogen content across all treatments was relatively uniform, with values ranging from 0.09 to 0.11. The treatment without EFB (T0) recorded a value of 0.11±0.02, while T1 and T2 showed values of 0.09±0.00 and 0.10±0.02, respectively. These results indicate that before the treatments produced a significant effect, soil nitrogen status among treatments was still at a relatively similar level.

At the December 2023 observation, soil nitrogen content decreased in all treatments, with a more pronounced decline in treatments T1 and T2, which showed values of 0.08±0.01 and 0.08±0.02, respectively. In contrast, treatment T0 maintained a slightly higher value of 0.09±0.02. The decrease in soil nitrogen in treatments receiving EFB indicates the occurrence of an early phase of nitrogen immobilization. Nitrogen immobilization is a condition in which mineral nitrogen in the soil is used by microorganisms to support the decomposition of organic materials with a relatively high C/N ratio (Cao et al., 2021). At this stage, nitrogen is not lost from the system but is temporarily bound in microbial biomass, resulting in lower measured soil nitrogen levels.

Table 1. Soil nitrogen content across different treatments and observation times

Treatment	Soil nitrogen content			
	August 2023	December 2023	April 2024	August 2024
T0	$0.11{\pm}0.02^{bcd}$	$0.09{\pm}0.02^{cd}$	$0.11{\pm}0.03^{bcd}$	$0.17{\pm}0.05^{a}$
T1	$0.09{\pm}0.00^{cd}$	$0.08{\pm}0.01^{d}$	$0.07{\pm}0.03^{d}$	$0.15{\pm}0.03^{ab}$
T2	$0.10{\pm}0.02^{cd}$	$0.08{\pm}0.02^{d}$	$0.10{\pm}0.03^{bcd}$	$0.13{\pm}0.04^{abc}$

Note: Values are means±SE. Different letters in the same row indicate significant differences (Tukey's test, α = 0.05)

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Differences among treatments became more evident at the April 2024 observation. Treatment T1 had the lowest soil nitrogen content (0.07±0.03), which was significantly lower than the other treatments. Meanwhile, treatments T0 and T2 recorded values of 0.11±0.03 and 0.10±0.03, respectively. The low soil nitrogen content in treatment T1 indicates that nitrogen released from EFB decomposition had not yet accumulated as measurable soil nitrogen but remained bound within the organic fraction (Wierzbowska et al., 2021) and had undergone turnover through soil microbial activity (Bossolani et al., 2023). Because burying EFB increases contact between organic material and soil, it enhances microbial activity and prolongs the nitrogen immobilization phase.

At the final observation (August 2024), soil nitrogen content increased in all treatments. Treatment T0 showed the highest value (0.17±0.05), and was significantly higher than the other treatments. Treatments T1 and T2 reached 0.15±0.03 and 0.13±0.04, respectively. This increase indicates that nitrogen mineralization had occurred. However, soil nitrogen content in the EFB treatments remained lower than in the control, suggesting that nitrogen released through mineralization is generally rapidly taken up by plants and soil microorganisms and therefore does not always accumulate as total soil nitrogen (Ward and Bradford, 2025).

Changes in oil palm leaf nitrogen content indicate plant responses to soil nitrogen dynamics resulting from EFB application. Leaf nitrogen content reflects the nitrogen that is absorbed and used by the plant and therefore does not always correspond directly with total soil nitrogen content. The results of the leaf nitrogen observations are presented in Table 2. At the initial observation (August 2023), leaf nitrogen content was relatively uniform across all treatments, with values ranging from 2.15 to 2.24%. Treatment T0 recorded a value of 2.15±0.06%, while treatments T1 and T2 showed values of 2.20±0.08% and 2.24±0.08%, respectively. These values reflect the initial nitrogen status of the plants before the EFB treatment had an effect.

At the December 2023 observation, leaf nitrogen content increased in all treatments, with the highest value recorded in treatment T2 (2.51±0.22%), followed by T1 (2.45±0.05%) and T0 (2.42±0.18%). This increase indicates that part of the nitrogen released during decomposition and mineralization had become available and was absorbed by the plants. Although soil nitrogen content in the EFB treatments was relatively lower during this period, available nitrogen appeared to be utilized more rapidly by plants rather than accumulated in the soil. The most pronounced increase in leaf nitrogen content occurred at the April 2024 observation, particularly in treatment T1, which reached the highest value of 2.62±0.10% and was significantly different from the other treatments. The treatment T2 also showed a relatively high value (2.50±0.10%), whereas T0 remained lower (2.44±0.17%). These results indicate that burying EFB improved plant nitrogen uptake efficiency. This improvement may occur through increased nitrogen availability in the root zone (Phillips et al., 2022).

At the final observation (August 2024), leaf nitrogen content decreased in all treatments, with values of 2.38±0.16% (T0), 2.33±0.13% (T1), and 2.28±0.12% (T2), respectively. This decline indicates that leaf nitrogen status is influenced not only by soil nitrogen availability but also by plant physiological factors, such as nitrogen redistribution to other plant organs and changes in nitrogen demand during growth (Li et al., 2025). Pearson correlation analysis in the final study period (August 2024) yielded a significant positive relationship between total soil nitrogen and leaf nitrogen content ($r = 0.73$; $p = 0.026$). These results indicate that the increase in soil nitrogen due to EFB application directly contributed to the improvement in nitrogen status of oil palm plants.

Table 2. Nitrogen content of oil palm leaves (Mean±SE) across different treatments and observation times

Treatment	Nitrogen content of oil palm leaves			
	August 2023	December 2023	April 2024	August 2024
T0	2.15±0.06^{d}	2.42±0.18^{bc}	2.44±0.17^{b}	2.38±0.16^{bc}
T1	2.20±0.08^{cd}	2.45±0.05^{b}	2.62±0.10^{a}	2.33±0.13^{c}
T2	2.24±0.08^{c}	2.51±0.22^{ab}	2.50±0.10^{ab}	2.28±0.12^{c}

Note: Values are means±SE. Different letters in the same row indicate significant differences (Tukey's test, α = 0.05)

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Effect of EFB application on earthworm population

The application of oil palm EFB significantly affected the dynamics of earthworm populations throughout the study period (Table 3). The earthworms identified in this study were *Pontoscolex corethrurus*, belonging to the family Glossoscolecidae. This species possesses an elongated cylindrical body with distinct segmentation and bilateral symmetry (James et al., 2019). *P. corethrurus* is recognized as a tolerant species capable of thriving under a wide range of environmental conditions and can become abundant in habitats with relatively low litter availability (Potapov et al., 2021). It has also been frequently reported in tropical oil palm plantation ecosystems (Azhar et al., 2024; Abdi et al., 2025; Al-Saedi et al., 2025) and tends to dominate earthworm communities compared with other species (Taheri et al., 2018).

In general, the population increased over time in all treatments, with the highest increase consistently observed in treatment T2 (surface-applied EFB). Analysis of variance showed that both treatment and observation time had significant effects on the earthworm population ($p < 0.05$). At the beginning of the observation, populations were relatively low, and there were no significant differences among treatments, reflecting the poor organic matter content of the Spodosols. Significant differences began to emerge in December 2023 and became more apparent in subsequent observations, with the peak population in T2 reaching 19.33 individuals m^{-2} in August 2024, markedly higher than in T1 and T0. This increase highlights the importance of surface-availability soil organic matter as the primary food source and habitat supporting earthworm activity (Vršič et al., 2021).

The earthworm population showed different responses to the organic material management treatments throughout the observation period. During the first two sampling times (August and December 2023), earthworm populations were still low and not significantly different among treatments. This indicates that soil biota requires an adaptation period following EFB application before population increases can occur. Significant differences began to appear in April 2024, when treatment T2 caused a clear increase in population compared with T0 and T1. This pattern continued until August 2024, with the highest population observed in T2 (19.33±16.49 individuals m^{-2}). This result shows that placing organic material on the soil surface provides a more favorable habitat, food source, and suitable microhabitat conditions for earthworms.

As a surface mulch, EFB also helps maintain soil moisture, stabilize temperature, and create suitable microhabitats for earthworms (Supriatna et al., 2022). In contrast, in T1, earthworm population increases were slower and not significantly different from the control until the end of the observation. Semi-anaerobic conditions in the subsurface layer are less favorable for earthworm activity and reproduction (Tao et al., 2018). Therefore, T1 did not show significant differences. Meanwhile, in T2, a significant difference in earthworm population was already observed since April 2024.

The earthworm population increased progressively during the observation period, with a significant rise after 8 to 12 months of EFB application, especially in T2. This increase has important implications for soil ecosystem functions. As ecosystem engineers, earthworms improve soil structure through bioturbation, increase water infiltration, accelerate nutrient cycling, and enrich soil organic matter (Ahmed and Al-Mutairi, 2022; Ratsiatosika et al., 2024). In addition, positive interactions with decomposer microorganisms can enhance mineralization efficiency and create ecological feedback that strengthens long-term soil fertility (Gutierrez Al-Khudhairy et al., 2023).

Organic matter decomposition by earthworms leads to the formation of casts, while their digestive activity, soil particle aggregation, and movement redistribute SOC throughout the soil (Iordache, 2023). The process of residue fragmentation and the formation of nutrient-rich casts (worm droppings) encourages nitrogen

Table 3. Earthworm population (individuals m^{-2}) across different treatments and observation times

Time	T0 (Control)	T1 (Incorporated)	T2 (Surface)
August 2023	0.74 ± 1.51^{b}	0.67 ± 2.00^{b}	0.89 ± 2.03^{b}
December 2023	1.78 ± 2.54^{b}	0.67 ± 1.00^{b}	3.78 ± 2.91^{b}
April 2024	0.89 ± 1.45^{b}	3.11 ± 4.01^{b}	14.44 ± 6.15^{a}
August 2024	4.44 ± 2.60^{b}	5.56 ± 4.22^{b}	19.33 ± 16.49^{a}

Note: Values are means±SE. Different letters in the same row indicate significant differences (Tukey's test, α = 0.05)

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mineralization, thereby increasing the concentration of plant-available nitrogen (Tecimen et al., 2021). These findings confirm that surface spreading of EFB is the most effective strategy to increase earthworm populations and improve organic residue management in oil palm plantation Spodosol soils.

In general, organic carbon content was positively and significantly correlated with earthworm population under EFB treatments, while a weak negative correlation was observed in the control. This confirms that organic material addition plays an important role in enhancing biological activity through positive feedback between organic carbon content and soil biota activity. Increasing SOC supports the growth of microorganisms that serve as food for earthworms, while earthworm activity accelerates organic matter decomposition and nutrient cycling (Guo et al., 2019; Ma et al., 2022).

In T0 (r = -0.35; p = 0.0337), the weak negative correlation indicates that naturally increasing soil carbon without regulated EFB addition is not sufficient to support earthworm populations. Acidic conditions, low organic matter content, and limited biological activity in Spodosols keep populations low even when carbon content increases slightly. In T1 (r = 0.45; p = 0.0061), the correlation was positive but weak, suggesting that EFB incorporation has a positive effect on earthworm populations.

In T2 (r = 0.60; p = 0.0001; n = 36), the strong positive correlation indicates a close relationship between the increase in SOC and earthworm population (Figure 3). Surface application of organic material provides direct access for earthworms and helps maintain soil moisture and temperature, thereby creating optimal microhabitat conditions (Radics et al., 2022; Yaseen and Abdulqadir, 2024). This makes the surface-spreading method the most effective for stimulating earthworm activity and population growth. The differences in correlation strength among treatments show that the effectiveness of increasing earthworm populations is determined not only by the amount of organic material, but also by the application method. The strongest correlation in T2 confirms that applying organic material on the soil surface is the most efficient strategy to improve soil biological functions in Spodosols.

Effect of EFB application on oil palm productivity

The results of Tukey's HSD post hoc test at the 5% significance level (Table 4) indicate that the application of oil palm EFB had a significant effect on FFB productivity. The treatment without EFB application (T0) resulted in the lowest productivity, at 10.63 tons ha^{-1}, and was significantly different from T2. In contrast, the treatment in which EFB was incorporated into the soil (T1) produced an intermediate productivity value (12.80 tons ha^{-1}) and was not statistically different from either T0 or T2, as indicated by the same significance letter (ab). The highest productivity was observed under the T2 treatment, yielding 13.31 tons ha^{-1}. The significant difference between T2 and T0 suggests that the presence of EFB generally enhances oil palm productivity; however, its effectiveness is strongly influenced by the application method. These findings emphasize that not only the amount of organic material applied, but also its placement in the field, plays a crucial role in determining crop yield responses.

Treatment T2 is presumed to create more favorable soil conditions for oil palm growth.

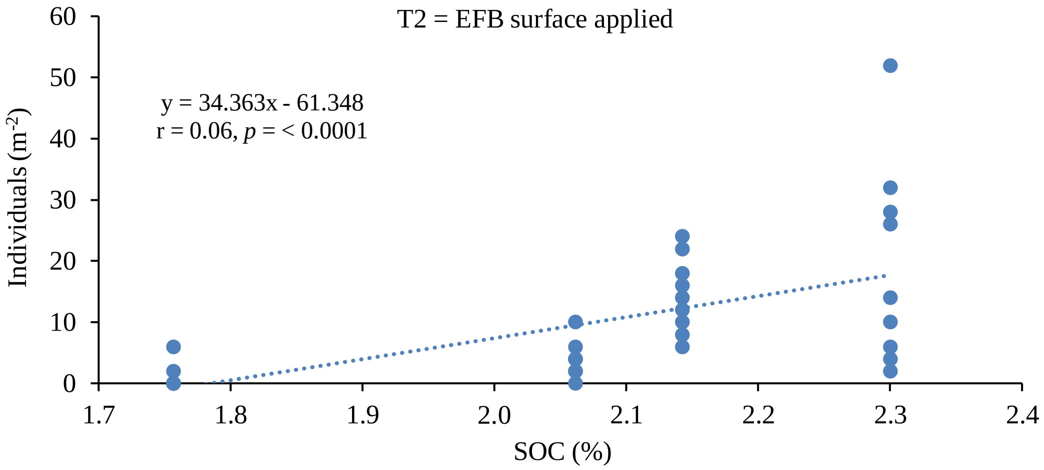

Figure 3. Relationship between SOC content and earthworm at a depth of 0-20 cm for T2

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Table 4. Post hoc test results for the effect of EFB application on FFB productivity

Treatment	FFB yield (tons ha^{-1})	SE	Significant letter
T0	10.63	±0.63	b
T1	12.80	±0.71	ab
T2	13.31	±0.51	a

Note: Values are means of 6 months of harvest (n = 9). SE = Standard error. Different letters indicate significant differences according to Tukey's HSD test (α = 0.05)

Organic mulching has been widely reported to reduce evaporation, maintain soil moisture, and improve the physical properties of the topsoil layer (Lopes et al., 2025). These effects are particularly important during dry periods by alleviating water stress and supporting plant physiological processes (Demo and Asefa Bogale, 2024; Vanella et al., 2025). Decomposition of EFB applied on the soil surface occurs relatively more slowly than that of EFB incorporated into the soil. This slower mineralization process allows nutrients to be released gradually and more in line with plant demand. Such synchronization between nutrient availability and plant uptake is believed to contribute to increased FFB productivity (Noirot et al., 2022). Thus, EFB functions not only as a nutrient source but also as a regulator of nutrient dynamics in the soil.

In the T1, decomposition tends to proceed more rapidly due to increased soil microbial activity. This condition may lead to temporary nitrogen immobilization, whereby available soil nitrogen is utilized by microorganisms for organic matter decomposition, thereby reducing nitrogen availability to plants during the early growth stages (Rosenani et al., 2016). This phenomenon may explain why productivity gains under T1 were lower than under T2, although absolute yields remained higher than under T0. From an operational and economic perspective, T2 also offers additional advantages. Surface application of EFB is relatively simpler and requires lower costs compared to incorporation using heavy equipment, such as a PC 50 mini excavator for soil excavation and backfilling as performed in the T1 treatment. By combining the highest productivity and more efficient operational costs, the T2 method provides superior agronomic and economic benefits.

CONCLUSIONS

The application of EFB improved soil organic carbon levels, increased earthworm abundance, and altered nitrogen dynamics in Spodosols under oil palm cultivation. Surface application of EFB was consistently more effective than incorporation in stimulating biological activity, promoting carbon stabilization, and increasing nutrient availability. By contrast, incorporation mainly accelerated short-term mineralization processes. Although total soil nitrogen declined temporarily due to microbial immobilization, nitrogen concentrations in oil palm leaves increased, indicating more efficient plant nitrogen uptake. These improvements in soil conditions were reflected in higher FFB yields, particularly under surface-applied EFB. Overall, surface application of EFB can be recommended as a sustainable management strategy to improve soil quality, nutrient cycling, and oil palm productivity, with clear benefits for long-term soil fertility in Spodosols.

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