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Research Paper

Biochar and Solid Decanter Improve Selected Soil Chemical Properties and Leaf Nutrient Status of Oil Palm Seedlings under Reduced NPK Fertilization

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Abstract

Oil palm seedling growth in acid mineral soils is often constrained by low soil fertility and limited nutrient retention, making organic amendments a potential strategy to improve growing media quality while reducing mineral fertilizer input. This study evaluated the effects of biochar and solid decanter, applied individually or in combination, on soil chemical properties and leaf nutrient status of oil palm seedlings under reduced compound mineral fertilizer rates. The experiment was arranged in a non-factorial randomized block design with seven treatments and four replications. The treatments were P0: without soil amendment + 100% NPK fertilizer; P1: $0.6\ \mathrm{kg\,plant^{-1}}$ solid decanter + 75% NPK fertilizer; P2: $0.6\ \mathrm{kg\,plant^{-1}}$ solid decanter + 50% NPK fertilizer; P3: $1.5\ \mathrm{kg\,plant^{-1}}$ biochar + 75% NPK fertilizer; P4: $1.5\ \mathrm{kg\,plant^{-1}}$ biochar + 50% NPK fertilizer; P5: $0.6\ \mathrm{kg\,plant^{-1}}$ solid decanter + $1.5\ \mathrm{kg\,plant^{-1}}$ biochar + 75% NPK fertilizer; and P6: $0.6\ \mathrm{kg\,plant^{-1}}$ solid decanter + $1.5\ \mathrm{kg\,plant^{-1}}$ biochar + 50% NPK fertilizer. After 14 weeks of treatment application, the treatment packages significantly affected soil organic carbon, total soil nitrogen, leaf phosphorus concentration, and soil exchangeable potassium. Soil organic carbon increased from 1.33% in the control to 5.83% in the combined biochar and solid decanter treatment with 50% NPK fertilizer. Total soil nitrogen also increased from 0.13% to 0.49% under the same treatment. However, soil pH, soil available phosphorus, leaf nitrogen, and leaf potassium were not significantly affected. These findings indicate that the integrated amendment-fertilizer packages, particularly the combination of biochar + solid decanter + 50% NPK fertilizer, improved soil organic carbon and total soil nitrogen and supported selected nutrient parameters, including leaf phosphorus concentration and soil exchangeable potassium, under a 25% to 50% reduction in the recommended NPK fertilizer rate.

Keywords

organic amendment; nutrient buffering; fertilizer efficiency; palm oil mill by-products; growing media.

1. INTRODUCTION

The nursery stage is a critical phase in oil palm cultivation because seedling quality at the early stage strongly influences plant vigor after transplanting to the field. At this stage, the quality of the growing medium is a fundamental factor, particularly when seedlings are grown in acid mineral soil. Acid soils are generally characterized by low pH, low base saturation, increased risk of base cation losses, high exchangeable aluminium, and limited fertilizer-use efficiency. In oil palm nurseries, amelioration of soil acidity has been shown to improve seedling and progeny performance; therefore, soil chemical constraints should not be regarded as a secondary issue during the nursery stage, but rather as an early determinant of growth success and nutrient-use efficiency (Cristancho et al., 2011; Mahmud and Chong, 2022; Radin et al., 2017).

Under such conditions, mineral fertilization alone does not always ensure an optimum response. Fertilizer effectiveness is determined not only by the amount of nutrients applied, but also by the ability of the growing medium to retain, release, and balance nutrients within the root zone. At the same time, high dependence on conventional chemical fertilizers is associated with economic burdens and environmental risks, making approaches that combine fertilizers with organic amendments increasingly important. Wang et al. (2022) and Rombel et al. (2022) reviewed the development of biochar-based fertilizer systems, including biochar-compost mixtures and biochar-based slow-release fertilizers, due to their ability to improve fertilizer efficiency, maintain nutrient availability for longer periods, and reduce nutrient losses compared with systems that rely solely on readily soluble mineral fertilizers.

Among various organic amendments, biochar is highly relevant for acid mineral soils. Recent reviews indicate that alkaline, porous, and carbon-rich biochar can reduce both active and exchangeable acidity while improving soil acid-buffering capacity. Biochar can also directly and indirectly increase phosphorus availability through changes in soil physical, chemical, and biological properties, and it may strengthen nitrogen retention within certain pH ranges in acid soils. In tree-based systems, the benefits of biochar have also been comprehensively summarized; however, the response remains strongly influenced by biochar type, application rate, soil properties, and plant species. Therefore, verification in oil palm nursery systems remains necessary (Antonangelo et al., 2025; Liu et al., 2025; Qian et al., 2023; Zhang et al., 2025).

In oil palm, experimental evidence on biochar has begun to develop, although it remains limited. Radin et al. (2017) evaluated EFB biochar, compost, and biochar-compost mixtures under 75% and 100% recommended fertilizer rates and reported improvements in polybag media chemical properties and reduced $NH_4{-}N$ leaching. Hwong et al. (2022) showed that EFB biochar improved growth, biomass, nutrient uptake, and soil CEC in oil palm seedlings, while Tugiman et al. (2024) further emphasized the role of oil palm biomass-derived biochar in improving nutrient retention in seedling media. Meanwhile, Azis et al. (2024) examined EFB biochar combined with nitrogen fertilization in peat soil and focused on nutrient leaching and nutrient uptake. Studies on oil palm decanter cake or solid decanter have also reported its potential as a bio-organic medium or nutrient source for plant growth, but this line of research has generally been separated from biochar-based amendment strategies (Embrandiri et al., 2016; Hashim, 2021; Prasetyo et al., 2023).

Taken together, these studies indicate that two research gaps remain open. First, the available oil palm nursery literature is still dominated by biochar as a single amendment or biochar combined with compost or N fertilizer, rather than biochar directly combined with solid decanter. Second, previous studies have more commonly emphasized seedling growth, nutrient uptake, or nutrient leaching, whereas simultaneous evaluation of soil pH, organic C, total N, available P, exchangeable K, and leaf N, P, and K concentrations under 25% to 50% reduced NPK fertilization remains limited. Therefore, the combination of biochar and solid decanter in acid mineral soil represents a specific amendment strategy to improve growing medium quality while reducing mineral fertilizer input.

The scientific value of combining biochar and solid decanter lies in both their complementary functions in the growing medium and their relevance to palm oil mill residue valorization. Oil palm empty fruit bunches are among the most abundant palm oil mill residues and can be converted into biochar through pyrolysis, providing a carbon-rich material with porous structure, reactive surfaces, and nutrient-retention capacity (Rahayu et al., 2021; Wang et al., 2022; Rombel et al., 2022). In contrast, solid decanter or decanter cake is an organic-rich residue that can contribute organic matter and nutrients to the seedling medium. Combining these two materials may therefore integrate the stabilizing and nutrient-retention functions of biochar with the nutrient-supplying function of solid decanter. This approach also supports circular bioeconomy principles by converting locally available palm oil mill by-products into value-added nursery inputs and reducing dependence on mineral NPK fertilizer (Siagian et al., 2024).

2. EXPERIMENTAL SECTION

2.1 Research Location and Biomaterial Use

The study was conducted at the Field Laboratory of Institut Teknologi Sawit Indonesia (3.6159° N; 98.7103° E). Soil, amendment, and leaf tissue analyses were conducted at the PT. Socfin Indonesia Laboratory. The soil used as the growing medium was collected from an area that, based on the exploratory soil resource map of the Medan sheet, belongs to the Kandiudults-Dystrudepts map unit located in Bangun Purba District, Deli Serdang Regency, North Sumatra (Menteri Pertanian, 2020). Soil sampling was conducted diagonally at five sampling points within a 1-ha area from a depth of 0-45 cm. This depth was selected to represent the topsoil to shallow subsurface layer, which is part of the active solum and remains relevant for nutrient storage, soil reaction, and early root development.

The initial soil characteristics obtained from laboratory analysis were pH H_2O 4.26, organic C 1.52%, sandy loam texture with 58.38% sand, 21.91% silt, and 19.72% clay, CEC 25.34 me $100g^{-1}$, total N 0.03%, total P 0.25%, and total K 0.29%.

The biochar used in this study was produced through low-temperature pyrolysis at approximately 250°C for 2 h under limited oxygen conditions, followed by drying, grinding, and sieving through a 20-mesh sieve. This temperature was selected to produce a low-temperature carbonized material that retained relatively high functional-group reactivity and nutrient-retention potential for use as a nursery growing-medium amendment. Although 250°C is at the lower boundary of thermochemical biomass conversion and may overlap with the torrefaction range, the material is referred to in this study as low-temperature biochar because it was obtained from thermochemical conversion of biomass under oxygen-limited conditions and was used for soil improvement purposes (International Biochar Initiative, 2015; Tumuluru et al., 2011; Tomczyk et al., 2020; Septiana et al., 2018).

The biochar and solid decanter was sieved through a 20-mesh sieve before use. The characteristics of these two materials, based on laboratory test results, show that: The biochar had pH 9.88, organic C 39.76%, moisture content 26.05%, CEC 52.76 me $100g^{-1}$, N 0.4729%, P 0.39% and K

6.02%. The solid decanter had pH 6.5, organic C 42.38%, moisture content 29.99%, CEC 37.71 me $100g^{-1}$, N 1.475%, P 0.49% and K 1.58%.

2.2 Experimental Design

The experiment was arranged in a non-factorial randomized block design with seven treatment levels and four replications, resulting in 28 experimental units. The blocks were established based on the initial condition of the seedlings and the row position of the polybags in the field nursery area. This arrangement was intended to control possible variability arising from initial seedling uniformity as well as environmental heterogeneity around the experimental plot, including differences in surrounding vegetation cover and related microenvironmental conditions. Each block contained all seven treatment packages, and the treatments were randomized within each block.

The treatments were structured as integrated amendment-fertilizer packages to represent practical nursery management options under reduced NPK fertilization. Therefore, the treatment effects in this study were interpreted as the overall response of each amendment-fertilizer package, rather than as separate main effects or statistical interactions among biochar, solid decanter, and NPK fertilizer rate. The treatment composition is presented in Table 1.

Table 1. The composition of treatments applied to oil palm seedlings grown in acid mineral soil under reduced NPK fertilization

Treatment	Soil (kg/plant)	Biochar (kg/plant)	Solid decanter (kg/plant)	NPK rate*
P0	9.0	0.0	0.0	100%
P1	9.0	0.0	0.6	75%
P2	9.0	0.0	0.6	50%
P3	9.0	1.5	0.0	75%
P4	9.0	1.5	0.0	50%
P5	9.0	1.5	0.6	75%
P6	9.0	1.5	0.6	50%

Table note: * Percentage of the recommended NPK rate for oil palm seedlings.

It should be noted that the treatments in this study were arranged as integrated amendment-fertilizer packages rather than as a factorial combination of biochar, solid decanter, and NPK fertilizer rate. Therefore, the observed responses should be interpreted as the overall effects of each treatment package relative to the 100% NPK control, not as separate main effects or statistical interactions among the individual components. This interpretation is important because the study was designed to evaluate practical nursery amendment packages under reduced NPK fertilization.

2.3 Cultivation Procedures

The growing media were prepared according to the treatments and incubated for two weeks. Polybags measuring 35 cm x 40 cm were used to grow 16-week-old oil palm seedlings of the D x P Simalungun variety. The polybags were arranged in the experimental area with a spacing of 90 x 90 x 90 cm. Plant maintenance included watering, pest and weed control, and fertilization.

Fertilization was carried out gradually using Rustika 12-12-17-2 fertilizer and kieserite, with the detailed schedule and rates for each treatment presented in Table 2.

2.4 Data Collection

After 14 weeks of treatment application, soil samples from the growing media were analyzed in the laboratory to determine organic C using the Walkley and Black method (Mouridi et al., 2023), soil pH using the electrometric method, total N using the Kjeldahl method, available P using the Bray II method, and exchangeable K using the ammonium acetate method. In addition, leaf N, P, and K concentrations were analyzed at the end of the observation period.

2.5 Data Analysis

The observed data were subjected to analysis of variance according to the non-factorial randomized block design. When the treatment effect was significant, mean differences were further tested using Duncan's Multiple Range Test (DMRT) at the 5% significance level. All statistical analyses were performed using SPSS 27.

3. RESULTS AND DISCUSSION

3.1 Effects of treatments on soil organic carbon and soil pH

Mean soil organic carbon differed significantly after 14 weeks of treatment application. Soil organic carbon increased from 1.33% in P0 to 1.56% in P1, 2.45% in P2, 3.19% in P3, 3.46% in P4, 4.15% in P5, and reached 5.83% in P6. In contrast, the treatments did not significantly affect soil pH. Soil pH measured in KCl ranged from 3.43 to 3.80 and did not differ significantly among treatments (Figure 1). This pattern indicates that the treatment response was more clearly reflected in soil organic carbon accumulation than in changes in soil acidity.

The increase in soil organic carbon in this study was strongly consistent with the characteristics of the materials used, as biochar and solid decanter contained 39.76% and 42.38% organic carbon, respectively. In a broader context, Lee et al. (2022) showed that biochar application to various agricultural soils can increase soil organic carbon in the short term, while Tugiman et al. (2024) emphasized that oil palm biomass-derived biochar as a planting medium was associated with improvements in carbon content, pH,

Table 2. Schedule and rates of fertilizer application for each treatment

Seedling age (weeks)	Fertilizer	P0	P1	P2	P3	P4	P5	P6
19	Kieserite (g/plant)	5.00	3.75	2.50	3.75	2.50	3.75	2.50
20	Rustika 12-12-17-2 (g/plant)	10.00	7.50	5.00	7.50	5.00	7.50	5.00
21	Kieserite (g/plant)	5.00	3.75	2.50	3.75	2.50	3.75	2.50
22	Rustika 12-12-17-2 (g/plant)	15.00	11.25	7.50	11.25	7.50	11.25	7.50
23	Kieserite (g/plant)	7.50	5.625	3.75	5.625	3.75	5.625	3.75
24	Rustika 12-12-17-2 (g/plant)	15.00	11.25	7.50	11.25	7.50	11.25	7.50
25	Kieserite (g/plant)	7.50	5.625	3.75	5.625	3.75	5.625	3.75
26	Rustika 12-12-17-2 (g/plant)	15.00	11.25	7.50	11.25	7.50	11.25	7.50
28	Rustika 12-12-17-2 (g/plant)	15.00	11.25	7.50	11.25	7.50	11.25	7.50
30	Rustika 12-12-17-2 (g/plant)	20.00	15.00	10.00	15.00	10.00	15.00	10.00

CEC, porosity, and nutrient availability. In oil palm nursery systems, Radin et al. (2017) also reported that a biochar-compost mixture derived from oil palm waste improved the chemical properties of polybag media. Therefore, the increase in organic carbon observed in this study can be understood as a direct consequence of the addition of carbon-rich materials into the growing medium, either as biochar or solid decanter. In this regard, solid decanter not only functions as an organic amendment but also aligns with the findings of Embrandiri et al. (2016) and Hashim (2021), who identified oil palm decanter-derived materials as relevant sources of organic matter and nutrients for growing media.

The treatment pattern showed that the increase in soil organic carbon tended to be greater in treatments involving the combined application of biochar and solid decanter, especially P5 and P6. This finding is agronomically important because, at the nursery stage, increased organic carbon in the growing medium indicates an increase in organic components that can improve medium quality through both stable carbon addition and more readily decomposable organic matter. This pattern is also consistent with Hwong et al. (2022), who reported that oil palm biomass-derived biochar improved several soil properties and nutrient uptake by seedlings, although the magnitude of the response was strongly influenced by biochar quality.

Unlike soil organic carbon, soil pH did not change significantly even though the biochar used had a pH of 9.88 and CEC of 52.76 me $100g^{-1}$. This result indicates that alkaline biochar pH does not necessarily translate directly into a significant increase in bulk soil pH. The pH response of acid soils to biochar depends on biochar type, application rate, acid-neutralizing capacity, exchangeable base cations, contact time, and intrinsic soil properties, particularly soil CEC (Martinsen et al., 2015). In the present study, biochar was applied at 1.5 kg $plant^{-1}$ to 9 kg of acid mineral soil, and the amended media were incubated for two weeks before seedling establishment. Soil pH was evaluated after 14 weeks of treatment application and measured in KCl. Because KCl can displace part of the exchangeable H^+ and Al^{3+} from soil exchange sites, the measured pH reflected not only active acidity in the soil solution but also part of the exchangeable acidity. In acid mineral soil with relatively high CEC of 25.34 me $100g^{-1}$, alkaline components released from biochar may first be consumed to neutralize active and exchangeable acidity near biochar particles, while H^+ and Al^{3+} from soil exchange sites can replenish acidity in the soil solution. This buffering process can reduce the magnitude of measurable pH change in the bulk soil, especially within a relatively short soil-biochar contact period (Liu et al., 2025). In addition, the solid decanter had a near-neutral pH of 6.5, indicating that its direct contribution to soil pH amelioration was likely limited.

3.2 Effects of treatments on total N and leaf N

The initial total N content of the soil used as the growing medium was low, at 0.03%, while biochar and solid decanter contained 0.47% and 1.47% total N, respectively. After 14 weeks of application, the treatments significantly affected total soil N. Total soil N increased from 0.13% in P0 to 0.49% in P6. In contrast, leaf N concentration ranged from 4.60% to 5.35% and did not differ significantly among treatments (Figure 2). These results indicate that, during the early nursery phase, the nitrogen response appeared first as an increase in N reserves in the growing medium rather than as a change in leaf N concentration.

The pattern of total soil N in this study did not show a linear relationship with the NPK fertilizer rate. For each pair of treatments with the same amendment type, the 50% NPK rate resulted in higher total soil N than the 75% NPK rate, as shown by P2 > P1, P4 > P3, and P6 > P5. The

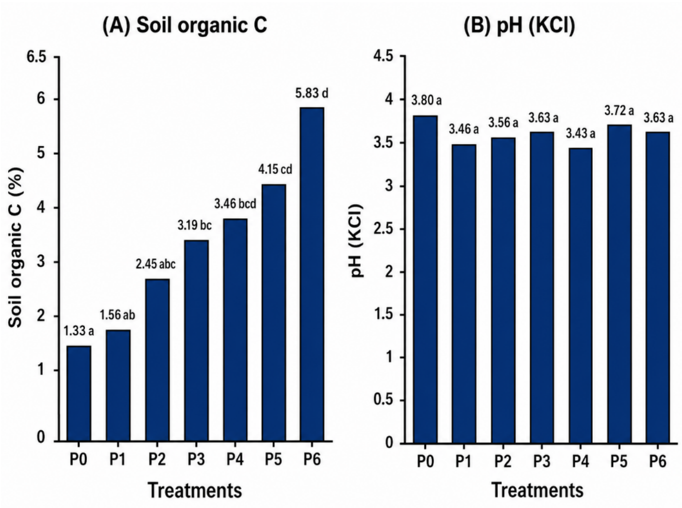

Figure 1. Mean soil organic carbon (SOC) and soil pH (KCl) after 14 weeks of treatment application

Note: P0 (without soil amendment + 100% NPK fertilizer), P1 (600 g solid decanter + 75% NPK fertilizer), P2 (600 g solid decanter + 50% NPK fertilizer), P3 (1,500 g biochar + 75% NPK fertilizer), P4 (1,500 g biochar + 50% NPK fertilizer), P5 (600 g solid decanter + 1,500 g biochar + 75% NPK fertilizer), and P6 (600 g solid decanter + 1,500 g biochar + 50% NPK fertilizer).

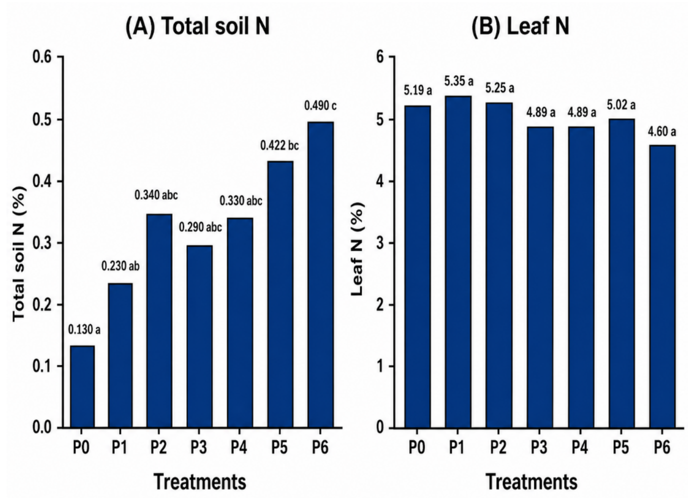

Figure 2. Mean total soil N and leaf N concentration after 14 weeks of treatment application

Note: P0 (without soil amendment + 100% NPK fertilizer), P1 (600 g solid decanter + 75% NPK fertilizer), P2 (600 g solid decanter + 50% NPK fertilizer), P3 (1,500 g biochar + 75% NPK fertilizer), P4 (1,500 g biochar + 50% NPK fertilizer), P5 (600 g solid decanter + 1,500 g biochar + 75% NPK fertilizer), and P6 (600 g solid decanter + 1,500 g biochar + 50% NPK fertilizer).

highest total soil N was obtained in P6, which combined biochar, solid decanter, and 50% NPK fertilizer. This finding indicates that soil N status at the end of the observation period was more strongly influenced by the presence and combination of amendments than by the mineral fertilizer rate alone. In other words, the addition of biochar and/or solid decanter has the potential to reduce the need for high mineral fertilizer rates because reduced NPK application was not followed by a decline in total soil N; in several treatments, it was instead associated with increased total soil N.

The increase in total soil N may have occurred through more than one mechanism. Solid decanter may have acted as an additional source of organic N because its N content was higher than that of biochar. At the same time, biochar may have helped retain N in the growing medium through physicochemical mechanisms. Gupta et al. (2024) showed that biochar can retain NH_4^+ through surface functional groups, such as carboxyl and ketone groups, as well as through increased cation exchange capacity, thereby reducing NH_4^+-N losses and NH_3 volatilization. Ahmed et al. (2019) also showed that biochar increased N retained in soil and reduced mineral N loss through leaching, while Jos et al. (2024) reported that the combination of biochar and chemical fertilizer in mineral soils increased NH_4^+ and NO_3^- retention and reduced N losses. Thus, the increase in total soil N in this study can be interpreted as the combined result of additional N supplied by the amendments and improved medium capacity to retain reactive N.

In addition to physicochemical mechanisms, microbial processes may also have contributed. DeLuca et al. (2024) explained that low-temperature biochar tends to retain more labile carbon fractions that can be utilized by microorganisms, thereby stimulating NH_4^+ and NO_3^- immobilization during the early phase after application. This explanation is relevant to the present study because the biochar was produced at approximately 250°C, suggesting that it may still contain available carbon and surface functional groups that support microbial activity. Bolan et al. (2023) further emphasized that biochar can serve as a good microbial carrier due to its pores, active functional groups, and C and nutrient contents that support microbial adhesion and colonization, while Huang et al. (2023) explained that biochar can improve the soil microenvironment and increase the abundance of microbial groups involved in nitrogen transformation.

In contrast to total soil N, leaf N concentration did not differ significantly among treatments. This result indicates that the increase in N in the growing medium was not immediately followed by changes in leaf N concentration during the 14-week observation period. Ahmed et al. (2019) also showed that biochar can increase N retention in soil without necessarily producing a large plant response, while DeLuca et al. (2024) emphasized that the effect of biochar on

N often appears first in N retention and transformation in the soil rather than in plant tissue, especially in short-term studies.

3.3 Effects of treatments on soil available P and leaf P

After 14 weeks of application, the treatments did not significantly affect soil available P but significantly affected leaf P concentration. Soil available P ranged from 551.33 to 747.26 mg P kg^{-1}, while leaf P concentration ranged from 0.19% to 0.27% (Figure 3).

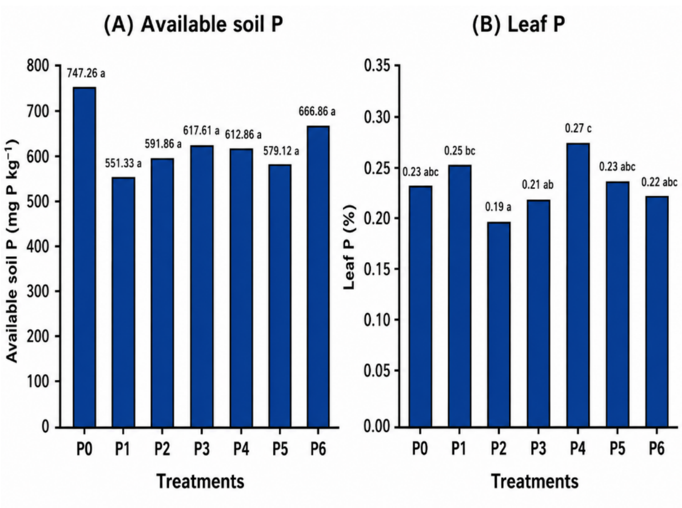

Figure 3. Mean soil available P and leaf P concentration after 14 weeks of treatment application

Note: P0 (without soil amendment + 100% NPK fertilizer), P1 (600 g solid decanter + 75% NPK fertilizer), P2 (600 g solid decanter + 50% NPK fertilizer), P3 (1,500 g biochar + 75% NPK fertilizer), P4 (1,500 g biochar + 50% NPK fertilizer), P5 (600 g solid decanter + 1,500 g biochar + 75% NPK fertilizer), and P6 (600 g solid decanter + 1,500 g biochar + 50% NPK fertilizer).

These results indicate that the phosphorus response in this study was more clearly reflected in plant nutrient status than in soil available P. Based on the DMRT results, P4 (0.27c) had the highest leaf P concentration and differed significantly from P2 (0.19a) and P3 (0.21ab), but did not differ significantly from P1 (0.25bc), P0 (0.23abc), P5 (0.23abc), and P6 (0.22abc). Meanwhile, P2 had the lowest value and differed significantly from P1 and P4. This pattern indicates that the plant P response did not follow a simple linear relationship with the NPK fertilizer rate. In the single solid decanter treatments, reducing the NPK rate from 75% to 50% was followed by a decrease in leaf P concentration, as shown by P1 > P2. In contrast, the single biochar treatments showed the opposite pattern, with P4 > P3. In the combined biochar + solid decanter treatments, P5 = P6 = P0. This pattern indicates that the combination of biochar and solid decanter did not always increase leaf P above the control, but it was able to maintain plant P status at a level comparable to 100% NPK even when the fertilizer rate was reduced to 75% or 50%.

Mechanistically, the absence of a significant difference in soil available P, despite significant differences in leaf P, can be explained by changes in phosphorus dynamics within the growing medium. Zhang et al. (2025) emphasized that increased organic carbon following biochar application can suppress the formation of insoluble P, reduce P adsorption, and support microorganisms that transform insoluble P into available forms. In this study, biochar and/or solid decanter may have helped release part of the adsorbed P and reduce P refixation, making P more accessible to plants even though changes in overall soil available P were not large or uniform enough to be detected as significant. This explanation is also consistent with Ibrahim et al. (2024), who showed that biochar can increase P availability and uptake through a combination of retention, gradual release, solubilization, and mineralization, although the magnitude of the effect strongly depends on biochar properties and soil conditions. Gupta et al. (2024) also supported the view that biochar can modify N and P dynamics differently depending on soil texture and biochar type, so changes in soil P are not always linear or uniform. This supports the interpretation that the non-significant response of soil available P in this study may still be consistent with improved P-use efficiency by plants. In other words, phosphorus changes may appear first in plant P status rather than in measured soil available P.

Treatment P4 showed that single biochar application with 50% NPK was the strongest treatment in increasing leaf P concentration, as it significantly exceeded P2 and P3. In contrast, the pattern P0 = P5 = P6 indicates that the combination of biochar and solid decanter functioned more as a buffer for plant P status. This means that the combined amendments were able to compensate for reduced NPK fertilizer rates, allowing leaf P status to remain comparable to that under the 100% NPK control. From an agronomic perspective, this finding suggests that palm oil waste-based organic amendments have the potential to reduce dependence on high rates of mineral P fertilizer during the nursery stage.

3.4 Effects of treatments on soil exchangeable K and leaf K

The initial K content of the soil used as the growing medium was 0.28 me $100g^{-1}$, while biochar and solid decanter contained 6.02% and 1.58% K, respectively. After 14 weeks of application, the treatments significantly affected soil K but did not significantly affect leaf K concentration (Figure 4).

Based on the DMRT test at the 5% significance level, P0 (3.11 me $100g^{-1}$) had the highest soil K and differed significantly from all other treatments. The next group consisted of P1 (2.65), P2 (2.99), and P5 (2.80), which did not differ significantly from one another. Lower values were observed

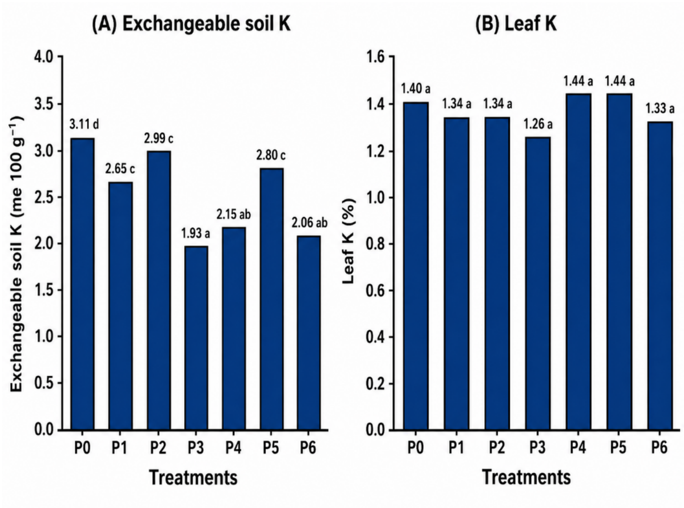

Figure 4. Mean soil exchangeable K and leaf K concentration after 14 weeks of treatment application

Note: P0 (without soil amendment + 100% NPK fertilizer), P1 (600 g solid decanter + 75% NPK fertilizer), P2 (600 g solid decanter + 50% NPK fertilizer), P3 (1,500 g biochar + 75% NPK fertilizer), P4 (1,500 g biochar + 50% NPK fertilizer), P5 (600 g solid decanter + 1,500 g biochar + 75% NPK fertilizer), and P6 (600 g solid decanter + 1,500 g biochar + 50% NPK fertilizer).

in P4 (2.15) and P6 (2.06), while P3 (1.93) had the lowest soil K. In contrast, leaf K concentration ranged only from 1.26% to 1.44% and did not differ significantly among treatments. This pattern indicates that the potassium response in this study was more clearly reflected in the soil compartment than in seedling leaf tissue.

The DMRT results for soil K reveal several important points. First, P0 > all other treatments, indicating that the 100% NPK control still produced the highest soil K status. Second, the group P1 = P2 = P5 shows that, in systems involving solid decanter, reducing the NPK rate from 75% to 50% did not significantly reduce soil K. Third, the group P4 = P6 shows that, at the 50% NPK rate, adding solid decanter to the biochar-based system did not significantly increase soil K compared with biochar alone. Fourth, P3, representing single biochar application with 75% NPK, had the lowest soil K, indicating that the high K content of biochar was not automatically translated into the highest exchangeable K in the soil at the end of the observation period. Soil K dynamics in this study therefore cannot be interpreted linearly based only on the K content of the amendment, but rather as the combined of amendment composition, NPK fertilizer rate, and the forms of K available in the soil system.

The highest exchangeable K observed in P0 indicates that the 100% NPK fertilizer treatment supplied K in a form that was more readily soluble and more rapidly reflected in the soil exchangeable K fraction than the amendment packages with reduced NPK fertilization. This finding suggests that, within the 14-week nursery period, biochar and solid decanter had not yet fully compensated for the reduction in mineral K input. The biochar and solid decanter used in this study contained measurable K concentrations of 6.02% and 1.58%, respectively. However, total K content in organic or biochar-based amendments does not necessarily represent the amount of K that is immediately released into the exchangeable pool. K release from biochar and organic amendments may occur gradually through dissolution, desorption, surface weathering, and organic matter decomposition, whereas mineral K fertilizer contributes more directly to short-term exchangeable K availability. Hartati et al. (2019) reported that increasing K fertilizer rates increased soil and plant K parameters, supporting the importance of readily available mineral K sources in short-term K availability.

Therefore, biochar and solid decanter should not be interpreted as direct short-term substitutes for mineral K fertilizer. Their role is more appropriately viewed as complementary amendments that may gradually contribute to K supply and improve nutrient retention over time. This interpretation is consistent with Ndoung et al. (2023), who examined the dynamics of K release from biochar-based fertilizers in soil, and Rodrigues et al. (2025), who showed that biochar-KCl composites can improve K availability although some pure biochars may remain less effective than KCl under certain conditions. Similarly, Xia et al. (2024) reported that co-application of biochar and K fertilizer improved soil K availability in a longer-term study, suggesting that the contribution of biochar to K dynamics may become more evident as a buffering or supporting effect rather than as an immediate replacement for mineral fertilizer.

3.5 Practical Implication

The practical value of the amendment packages lies in their potential to improve selected soil chemical properties while reducing mineral NPK input. However, because this study focused on agronomic responses and did not include economic analysis, the cost-effectiveness of applying 1.5 $kg\,plant^{-1}$ biochar and 0.6 $kg\,plant^{-1}$ solid decanter cannot yet be concluded. Any reduction in NPK fertilizer cost must be weighed against the costs of obtaining and processing the amendments, including residue collection, drying, pyrolysis, grinding, transport, labor, and application. Thus, the use of biochar and solid decanter may be more feasible where these materials are locally available and processing costs are low. Future studies should include cost-benefit ratio, labor requirements, and operational feasibility under commercial nursery conditions.

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

The integrated application of biochar, solid decanter, and reduced NPK fertilizer improved selected chemical properties of acid mineral soil used as oil palm seedling media. The treatments mainly increased soil organic carbon and total soil N, with the highest response obtained from the combination of biochar + solid decanter + 50% NPK fertilizer. The treatments also significantly affected leaf P concentration and soil exchangeable K, whereas soil pH, soil available P, leaf N, and leaf K were not significantly affected. The highest exchangeable K in the 100% NPK control indicates that mineral K fertilizer remained the most immediate source of exchangeable K during the 14-week nursery period. Overall, biochar and solid decanter have potential as complementary organic amendments to improve selected soil chemical properties and support selected nutrient parameters under reduced NPK fertilization.

4.2 Recommendation

Biochar and solid decanter may be considered as organic amendments to support reduced NPK fertilizer application in oil palm nurseries on acid mineral soils. Further studies should evaluate fertilizer-use efficiency and cost-benefit ratio to determine whether the application of biochar and solid decanter can provide agronomic and economic advantages under reduced NPK fertilization in commercial oil palm nurseries.

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