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RESEARCH PAPER

Effect of nano-compost from oil palm waste enriched with ZnO and SiO_2 nanoparticles on nursery growth of oil palm (*Elaeis guieensis Jacq.*)

Sama' Iradat Tito[1], Sri Gunawan[2], Enny Rahayu[2], Abdul Basit[3, 5], Anita Qur'ania[3, 5], Helda Syahfari[4] and Nurhidayati Nurhidayati[3, 5]*

[1]Biology Department, Faculty of Mathematic and Natural Sciences, Universitas Islam Malang, 65144, Indonesia
[2]Agrotechnology Department, Faculty of Agriculture, Institut Pertanian Stiper, 55584, Yogyakarta, Indonesia
[3]Agrotechnology Department, Faculty of Agriculture, Universitas Islam Malang, 65144, Indonesia
[4]Agrotechnology Department, Faculty of Agriculture, Universitas 17 Agustus 1945, Samarinda, Indonesia
[5]Center for Food Security Studies, Universitas Islam Malang, Indonesia

***Corresponding author's email:** nurhidayati@unisma.ac.id

Key Message: ZnO and SiO_2-enriched oil palm waste nano-compost significantly enhanced oil palm nursery growth by improving nutrient availability and nutrient uptake, increasing dry weight of plant, enabling reduced conventional fertilizer inputs while promoting sustainable. This approach improves the circular nutrient management in oil palm production systems especially in humid tropical soils.

Abstract

Oil palm nursery growth is constrained by low nutrient use efficiency and suboptimal growing media, while large amounts of oil palm industrial waste remain underutilized, necessitating the development of nanoparticle-enriched nano-compost as a sustainable fertilization strategy. This study evaluated the effects of nanoparticle-enriched nanocompost derived from oil palm empty fruit bunch (EFB) and solid decanter waste which enriched nanoparticles ZnO and SiO_2 on oil palm seedling growth in two soil types, Hapludult and Dystrudept. The experiment employed a factorial Randomized Block Design (RBD) with two factors: soil type (S_1 = Hapludult, S_2 = Dystrudept) and fertilization treatment (T_0 = Control (no treatment), T_1 = 100% NPK, T_2 = 100% nanoparticles enriched nanocompost (NEN), T_3 = 50% NPK+ 50% NEN, T_4 = 25% NPK+75% NEN). Results showed that both soil type and fertilization significantly affected all growth parameters. Interaction between soil type and fertilization treatment ($p<0.05$) significantly affected nutrient uptake, SPAD value, dry weight of plant, shoot and root. The best performance was observed in T_4 (25% NPK+75% NEN), which improved plant height, number of leaf sheaths, stem diameter, and length of the leaf sheaths compared to other treatments with an average increase of 20.7% compared to the control. Meanwhile, leaf area increased by 108.49% compared to the control. The growth performance of oil palm seedlings on hapludult soil was significantly higher ($p<0.05$) as 67.4% compared to Dystrudept soil. These findings highlight the potential of nano-compost derived from oil palm waste to enhance seedling growth while reducing chemical fertilizer dependence. Integrating nano-compost with NPK represents a promising strategy for sustainable nutrient management in oil palm nurseries.

Keywords: *Elaeis guineensis*, Main nursery, Nanocompost, Nanoparticles, Oil palm waste, Soil type

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Introduction

Oil palm (*Elaeis guineensis Jacq.*) is one of the most important tropical crops and the leading source of vegetable oil worldwide. Its economic significance continues to grow, particularly in Southeast Asia, where Indonesia and Malaysia together contribute over 85% of global palm oil production with plantations covering over 20 million hectares (Maluin et al., 2020). Despite its economic value, the oil palm industry faces increasing scrutiny regarding its environmental footprint, especially in terms of deforestation, soil degradation, and waste management. Large volumes of oil palm residues such as empty fruit bunches (EFB), palm press fiber, and palm oil mill effluent are generated annually, posing significant disposal and pollution challenges (Singh et al., 2013; Saputra et al., 2024). These residues are often underutilized and pose environmental disposal challenges. Recycling these by-products into compost has emerged as a sustainable strategy to reduce waste while improving soil fertility and nutrient availability (Haydar et al., 2024; Latif & Abbas, 2025). The conversion of these residues into value-added soil amendments represents a promising step toward sustainable intensification and a circular bioeconomy. Compost derived from EFB and other oil palm residues has been reported to enhance soil organic matter, nutrient content, and microbial activity, thereby promoting better root development and plant growth (Effendi et al., 2025). Nevertheless, conventional composting often suffers from low nutrient density, slow nutrient release, and inconsistent effects across soil types.

In recent years, nanotechnology has shown promising potential in agriculture for enhancing nutrient use efficiency, improving soil–plant interactions, and minimizing losses due to leaching or volatilization. Nanoparticles can serve as carriers for nutrients or act as catalytic agents that regulate nutrient transformation processes, resulting in a more controlled and efficient delivery to plants (Ardali et al., 2024; Nawadkar et al., 2024; Pudhuvai et al., 2024). Previous research on the application of nanocompost has been conducted in rice cultivation and has become a very important field of study because of its potential to increase the efficiency of nutrient use, increase crop yields, and reduce the use of inorganic fertilizers (Ávila-Quezada et al., 2022; Nurhidayati et al., 2024). The enrichment of compost with nanoparticles resulting in nano-compost combines the advantages of organic amendments and nano-enabled nutrient delivery systems. Such nano-composts can potentially enhance nutrient retention, increase microbial activity, and stimulate plant physiological responses (Asmawi et al., 2024). Despite the growing interest in nano-amended organic fertilizers, limited information is available on the performance of oil palm waste-derived nano-compost in the nursery stage, particularly under different soil conditions. This research was conducted to develop a sustainable fertilization approach for oil palm nurseries using nano-compost produced from oil palm industrial waste enriched with ZnO and SiO_2 nanoparticles. However, current literature provides limited evidence on the effectiveness and underlying mechanisms of nanoparticle-enriched compost in enhancing nutrient availability, uptake efficiency, and early growth of oil palm under nursery conditions. This study therefore delivers new applied and mechanistic insights into nano-enabled circular fertilization strategies for improving oil palm nursery performance. Soil type strongly influences the effectiveness of organic amendments and nutrient dynamics because of differences in texture, cation exchange capacity, and water-holding capacity (Manorama et al., 2024). Understanding how nano-compost interacts with varying soil types is crucial to optimizing its use in sustainable oil palm cultivation. This study used the Hapludults and Dystrudepts soil types originating from Central Kalimantan Province, Indonesia.

Central Kalimantan Province is one of the provinces in Indonesia that represents a major oil palm expansion area dominated by Hapludult and Dystrudept soils with inherent fertility constraints. Oil palm plantation land is characterized by low organic matter content as a result of long-term oil palm cultivation (Harahap & Fitra, 2020; Golicz et al., 2024). Both Hapludult and Dystrudept soils typically have a strongly acidic pH (<5), which adversely affects nutrient availability and microbial activity (Navarrete et al., 2013; Galgo & Asio, 2022). These soils often possess low CEC, limiting their ability to retain essential nutrients like potassium (K), calcium (Ca), and magnesium (Mg) (Piamonte et al., 2014; Osman, 2018; Mulyadi & Arruan, 2019). Hapludult soils are low phosphorus availability and other essential nutrients, while Dystrudept soils have low organic matter and weak nutrient retention, making them prone to leaching under high rainfall. These limitations often reduce fertilizer efficiency in oil palm nurseries, justifying their selection to evaluate nanoparticle-enriched nano-compost under marginal soil conditions (Navarrete et al., 2013; Mulyadi & Arruan, 2019).

On the other hand, the increasing demand for palm oil has prompted expansion of plantation areas and the intensification of nursery management practices to ensure high-quality seedlings with vigorous early growth. Proper nutrient management during the nursery stage is essential for establishing a healthy and productive plantation system (Akpo et al., 2014a; 2014b). Effendi et al. (2025) reported that the application of 200 g of EFB compost per plant combined with 60 g of NPK fertilizer increased the growth of oil palm seedlings in the main nursery. Therefore, this study aimed to (1) evaluate the growth response of oil palm seedlings to nano-compost derived from oil palm residues enriched with ZnO and SiO_2 Nanoparticles, (2) compare the performance of seedlings grown on two soil types, and (3) to explain the interaction between soil type and fertilization treatment using nanoparticles enriched nano-compost derived from palm oil industry waste and NPK fertilizer on the physiology of oil palm plants.

Materials and Methods

Experimental site and design

The experiment was carried out in a greenhouse in Sengonagung Village, Purwosari District, Pasuruan Regency which is located at approximately 7°44’32.9” S and 112°43’49.9” E, between February and October 2025. The study employed a factorial Randomized Block Design (RBD) with five replications. The first factor was soil type, consisting of two levels namely S_1: Hapludult and S_2: Dystrudept. The second factor was fertilization treatment, consisting of five levels namely T_0: Control (no fertilizer), T_1: 100% NPK fertilizer (recommended nursery dose), T_2: 100% nanoparticles-enriched nanocompost (NEN), T_3: 50% NPK+50% NEN, T_4: 25% NPK+75% NEN. This combination resulted in 10 treatment combinations (2 × 5), each replicated five times, and each replication had three plant samples. A total of experimental units were 150 pots.

Preparation of nanoparticle-enriched nanocompost

Empty fruit bunch (EFB) and solid decanter waste were collected from a palm oil mill in Central Kalimantan, Indonesia. The materials were shredded and pre-decomposed for 15 days before composting. A microbial inoculum containing *beneficial microorganisms* was added to accelerate lignocellulosic degradation. After 30 days of active composting, the composted material was dried and ground with a grinder to produce finer particles. The next step is to grind the fine compost again using a grinder mill to produce a powder with micron-sized particles. The micro-compost was enriched with ZnO and SiO_2 nanoparticles (≈100 nm) at a concentration of 200 mg kg^{-1} and 100 mg kg^{-1} compost respectively using a mixer. The homogenized mixture was matured for another 7 days to produce nanoparticle-enriched nanocompost (EFB + solid decanter). The resulting compost was analyzed for pH, total N, available P, exchangeable K, organic C, C/N ratio, and cation exchange capacity (CEC) following standard protocols (Okalebo et al., 2002). The result of laboratory analysis showed that the nano compost had pH (H_2O) = 10.36; C-organic = 30.39%; N-total = 2.83%; C/N ratio = 10.73, P_2O_5= 2.12%; K_2O= 2.56%, lignin = 11.52%; Polyphenol = 0.45% and cation exchange capacity = 49.48 cmol kg^{-1}.

Table 1 Characteristics of Hapludult and Dystrudept soil used in this study

Parameter	Hapludult	Criteria	Dystrudept	Criteria
pH (H_2O)	5.43±0.15	Acid	5.4±0.17	Acid
pH (KCl)	4.13±0.12	Acid	4.33±0.15	Acid
C-Organic (%)	0.68±0.02	Very low	0.61±0.04	Very low
Organic matter (%)	1.17±0.04	Very low	1.05±0.07	Very low
N-Total (%)	0.16±0.01	Low	0.07±0.01	Very low
C/N	4.15±0.16	Low	8.89±1.86	Low
P_2O_5 (%)	8.73±0.15	Very low	8.70±0.26	Very low
K_{dd} (cmol/kg)	0.20±0.02	Low	0.18±0.02	Low
CEC (cmol/kg)	9.76±0.94	Low	8.16±0.52	Low
% Sand	43.89±1.56	Soil texture Class: Clayey loam	69.74±2.66	Soil texture class: Sandy clay loam
% Silt	24.53±1.62		6.26±6.26	
% Clay	31.58±1.05		24.00±3.39	

Soil collection and characterization

Two soil types were collected from oil palm plantation areas in Central Kalimantan. The soils samples were air-dried, sieved (<2 mm), and analyzed for texture (hydrometer method), pH (1: 2.5 H_2O), organic carbon (Walkley–Black), total nitrogen (Kjeldahl), available phosphorus (Bray-1), exchangeable potassium (NH_4OAc extraction), and CEC (NH_4OAc 1N, pH 7.0) prior to use (Okalebo et al., 2002). The result of laboratory analysis was presented in the Table 1.

Plant materials and nursery management

Two types of soil samples from Hapludults and Dystrudepts that had passed a 2 mm sieve were weighed to 15 kg and then put into polybags measuring (35 cm × 45 cm) for each type of soil as much as 75 polybags. Nanoparticles enriched nanocompost treatments were applied at two days before transplanting. Uniform Sriwijaya variety oil palm seedlings with an age of 5 months from the pre-nursery were transplanted into polybags in size 35 cm × 45 cm. Chemical fertilizers were applied according to the schedule determined for Sriwijaya variety oil palm seedlings. The total dose of inorganic fertilizer applied to oil palm seedlings aged 5 months to 12 months for treatment 100% NPK (T_1) is 44 g N-P-K-Mg (15-15-6-4), 157 g N-P-K-Mg (12-12-7-2) and 22 g Kieserite ($MgSO_4$). For treatment T_3 and T_4, adjust to the predetermined percentage. Seedling growth is maintained for 7 months or the seedling age is 12 months. The nursery was maintained with daily watering to maintain about 70–80% of field capacity. Manual weeding and pest control were conducted regularly to ensure optimal seedling growth.

Growth observations

During 7 months after transplanting, data were collected on growth parameters included plant height, stem diameter, number of leaf sheaths and leaf area. Plant height was measured from the base of the stem to the tip of the tallest leaf using a measuring tape (cm), stem diameter was determined at the basal stem using a digital caliper (cm), the number of leaf sheaths was counted manually per plant, and leaf area was estimated using the method of measuring the length multiplied by the width of the leaf blade, then multiplied by the correction factor and the number of perfectly formed leaves (cm^2). These parameters were measured every month during the growth of oil palm seedlings. At the end of the observation period the plants were dismantled and the dry weight of total biomass, roots, root length and root volume were measured. Physiological parameters including chlorophyll index (SPAD value), nutrient uptake (NPK) and root–shoot ratio were also measured at the end of the observation.

Statistical analysis

Data were analyzed using two-way ANOVA to test the effects of soil type, fertilization treatment, and their interaction. When significant differences were observed ($p<0.05$), mean separation was conducted using Tukey's HSD test. Correlation and regression analyses were also performed to explore the relationship between nutrient uptake and plant growth parameters. All statistical analyses were performed using IBM SPSS Statistics v26 and R software v4.3.2.

Results

Seedling growth performance

The growth responses of oil palm seedlings were significantly influenced by both soil type and fertilizer treatments. However, the interaction between the two factors did not have a significant effect on the growth of oil palm seedlings. Seedlings grown on Hapludult (S_1) exhibited better growth compared to those on Dystrudept (S_2) measured by parameters of plant height, stem diameter, and leaf area (Fig. 1 A-C). The average increase in plant height and stem diameter of oil palm seedlings planted on Hapludult soil was 15.4% and 7.6%, respectively, compared to those on Dystrudept soil (Fig. 1 A-B), while the increase in leaf area of oil palm seedlings on Hapludult soil was 51.4% compared to those on Dystrudept soil (Fig. 1C). This indicated that the fertility advantage of Hapludult's higher clay content, soil pH, C-organic and CEC than Dystrudept (Table 1). The average increase in number of leaf sheaths and length of the leaf sheaths oil palm seedlings planted on Hapludult soil was 12.4% and 7.1%, respectively, compared to those on Dystrudept soil (Fig. 2 A-B). This indicated that the fertility advantage of Hapludult's higher clay content, soil pH, C-organic and CEC than Dystrudept (Table 1). The combination of 25% NPK+75% NEN significantly improved stem diameter and length of the leaf sheaths to the control and 100% NPK (Fig. 4 A-B). The average increase in stem diameter and length of the leaf sheaths of oil palm seedlings planted on these treatments (T3 and T4) were 21.45%, 21.3% and 87.05%, respectively, compared to the control (no treatment). Across fertilization treatments, the combination of 25-50% NPK+50%-75% NEN markedly improved plant height, number of leaf sheaths, and leaf area to the control and 100% NPK (Fig. 3 A-C). The average increase in plant height, number of leaf sheaths and leaf area, and of oil palm seedlings planted on these treatments (T3 and T4) were 21.45%, 21.3% and 87.05%, respectively, compared to the control (no treatment).

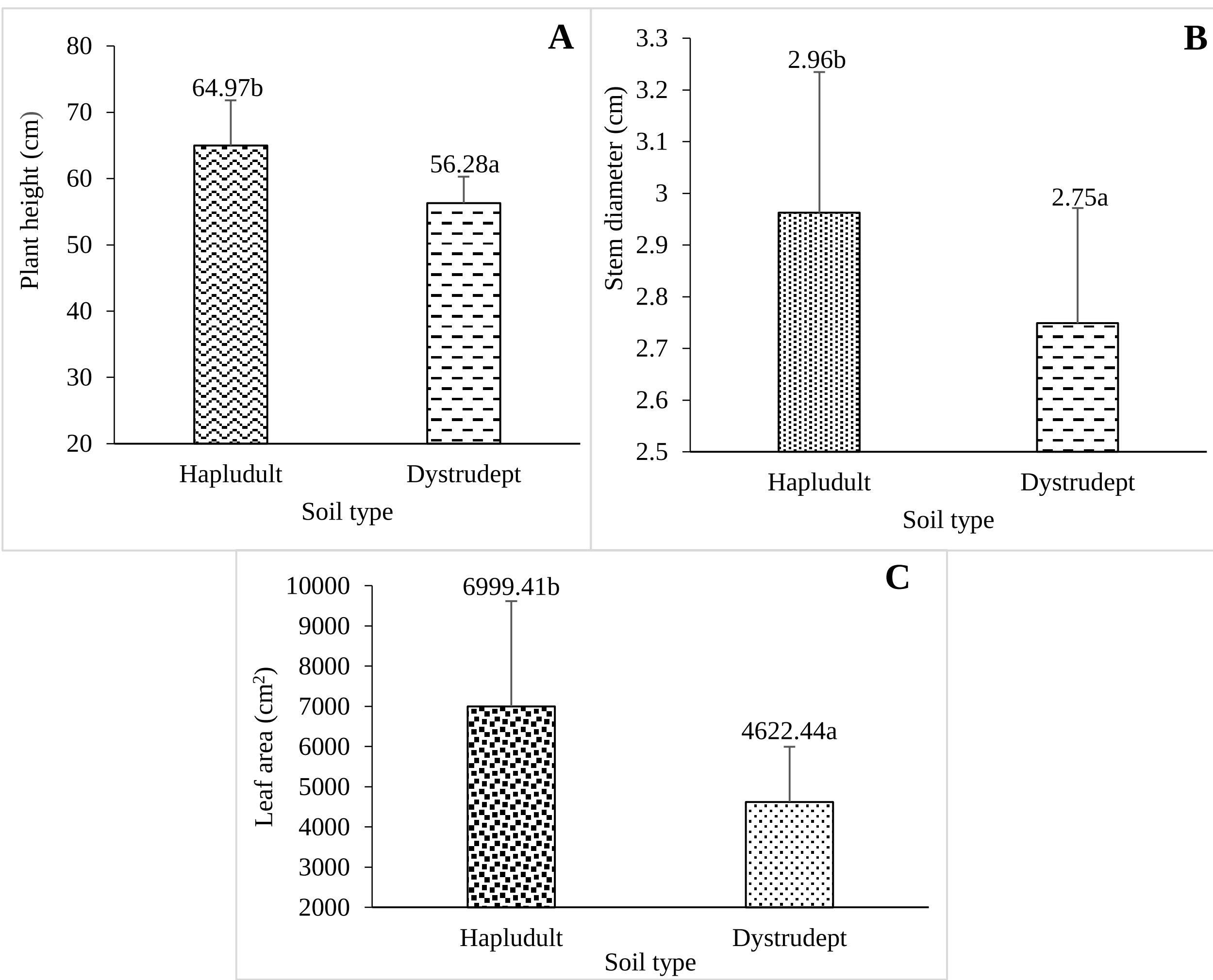

Fig. 1 Effect of soil types on plant height, stem diameter, and leaf area parameters of oil palm seedlings after 7 months

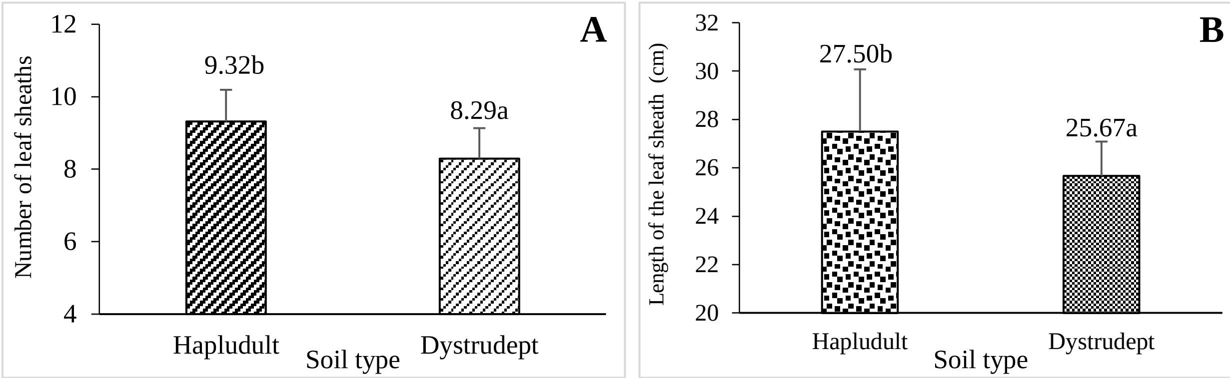

Fig. 2 Effect of soil types on number of leaf sheaths, and length of the leaf sheath of oil palm seedlings after 7 months

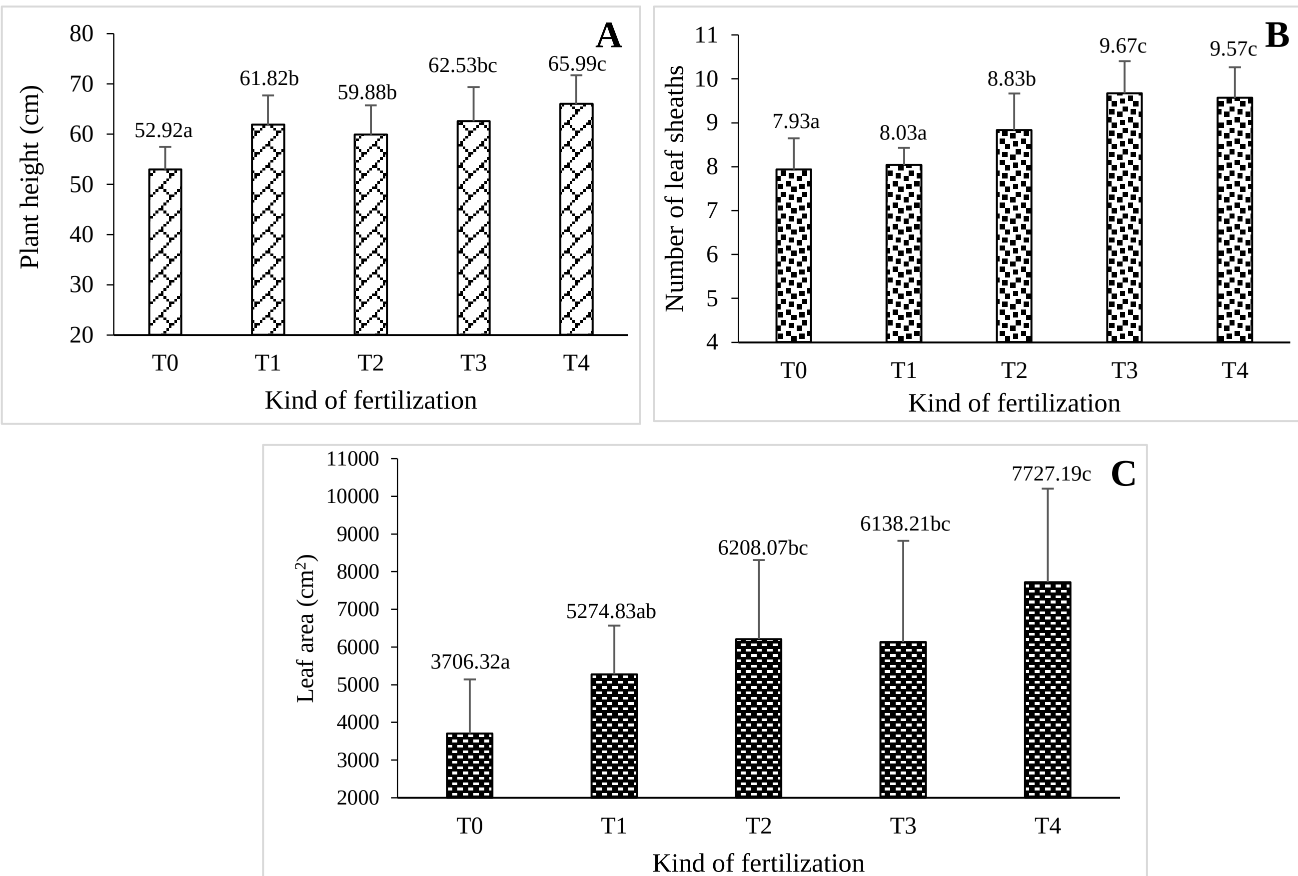

Fig. 3 Effect of fertilizer treatments on growth plant height, number of leaf sheaths, and leaf area of oil palm seedlings after 7 months

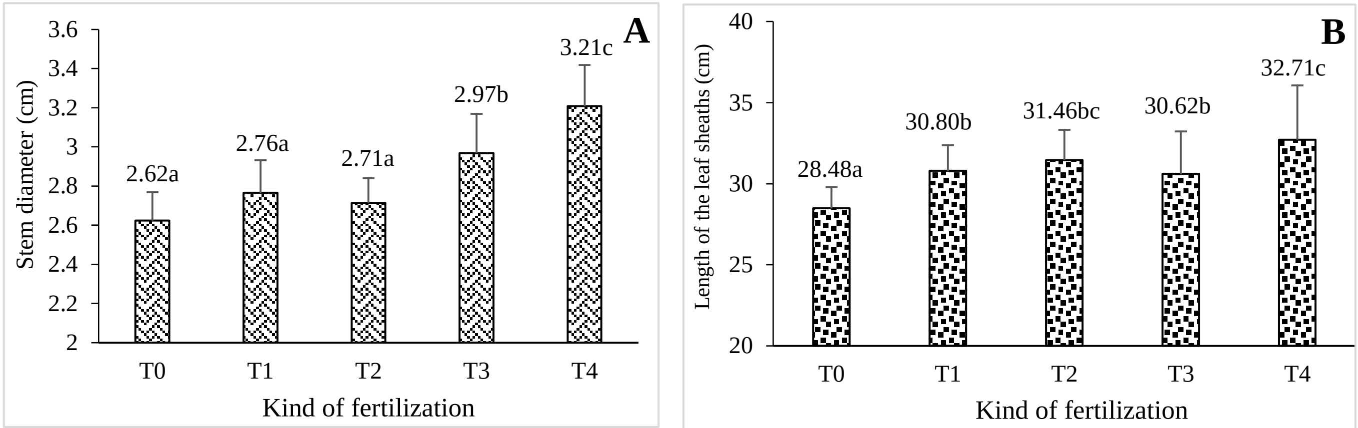

Fig. 4 Effect of fertilizer treatments on stem diameter and length of the leaf sheaths of oil palm seedlings after 7 months

Nutrient uptake and chlorophyll content (SPAD value)

Tukey test results showed that N, P, K uptake and SPAD Value were significantly influenced by the interaction between soil type and fertilizer treatment. In Hapludult and Dystrudept soils, treatment T_1 (100% NPK) produced the highest N uptake (0.14%) and was significantly different compared to the control and pure nanocompost-based treatments. This reflects that N, P, and K from inorganic fertilizers are in a readily available form, so they are directly absorbed by plants (Table 2). However, the combination treatments T_3 (50% NPK + 50% NEN) also showed relatively high N uptake and were not significantly different from T_1. In Dystrudept soil, the 100% NPK had the highest nutrient uptake. It indicated that soils with low nutrient binding capacity are highly dependent on stable nutrient availability in the root zone. For the SPAD value parameter, the T_3 treatment gives a higher SPAD value than the T_1 treatment (100% NPK) on the Dystrudept, but on the Hapludult, the SPAD value in the T_3 treatment (50% NPK and 50% NEN) has the same high value as the T_1 treatment (100% NPK). It indicated that nanocompost was able to maintain N uptake efficiency even though the NPK dose was reduced in Hapludult, so that it has a better impact on the level of leaf greenness than the 100% NPK treatment.

Table 2 Effect of soil type and fertilizer treatments on nutrient uptake and SPAD value of oil palm seedlings after 7 months

Soil type	Fertilization	N (%)	P (%)	K (%)	SPAD value
Hapludult (S1)	T0 (control)	1.91±0.02^{b}	0.12±0.03^{a}	2.86±0.04^{a}	65.80±4.32^{bc}
	T1 (100% NPK)	2.40±0.09^{c}	0.13±0.01^{a}	4.14+0.05^{bc}	73.68±4.66^{d}
	T2 (100% NEN)	1.96±0.17^{b}	0.28±0.01^{d}	4.95±0.06^{de}	73.71±6.27^{d}
	T3 (50% NPK+50% NEN)	3.75±0.09^{e}	0.48±0.01^{e}	4.58±0.55^{cd}	75.46±3.38^{d}
	T4 (25% NPK+75% NEN)	2.46±0.08^{c}	0.29±0.06^{d}	5.06±0.02^{e}	72.57±3.57^{cd}
Dystrudept (S2)	T0 (control)	1.53±0.06^{a}	0.10±0.01^{a}	2.74±0.09^{a}	53.54±3.31^{a}
	T1 (100% NPK)	3.05±0.11^{d}	0.12±0.03^{a}	4.08±0.01^{bc}	62.65±4.45^{b}
	T2 (100% NEN)	1.48±0.04^{a}	0.14±0.01^{a}	4.05±0.08^{bc}	54.65±3.87^{a}
	T3 (50% NPK+50% NEN)	2.81±0.14^{d}	0.25±0.01^{cd}	3.84±0.10^{b}	70.63±2.42^{cd}
	T4 (25% NPK+75% NEN)	3.08±0.16^{d}	0.19±0.02^{bc}	4.19±0.05^{bc}	67.72±2.07^{bc}
HSD 5%		0.03	0.28	0.06	0.42

Values followed by different letters within same columns differ significantly at $p < 0.05$ (Tukey's HSD).

Dry weight of oil palm biomass

Tukey's test results showed that the total dry weight of plant biomass, roots, shoots, and shoot/root ratio were significantly affected by the interaction between soil type and fertilizer treatment. In soil S_1 (Hapludult), the S_1T_4 treatment (75% NEN + 25% NPK) produced the highest total biomass (74.66 g) and was significantly different from the control (S_1T_0), S_1T_1 (100% NPK) and S_1T_2 (100% NEN), while treatments S_1T_3 and S_1T_4 were in the highest statistical group (Table 3). This indicates that substituting a significant portion of NPK with nanocompost significantly increases biomass accumulation in soils with chemical constraints such as acidity and nutrient fixation.

Conversely, in soil S_2 (Dystrudept), total biomass was generally lower than in Hapludult, reflecting limited nutrient and organic matter retention. However, S_2T_4 (47.63 g) showed a significant increase in biomass compared to the control (S_2T_0 = 22.50 g), confirming that nanocompost is also effective in soils with physical constraints and high nutrient leaching, although the response was more moderate than in S_1 (Table 3). The significant interaction between soil and fertilization indicated that the response to nanocompost was soil-dependent.

Root biomass increased with increasing nanocompost proportions, especially in Hapludult soil. Treatments S_1T_3 (15.91 g) and S_1T_4 (15.26 g) produced the highest root biomass and were significantly different from the control, indicating that nanocompost promotes the development of a stronger and more extensive root system. This is particularly important in acidic soils, as well-developed roots enhance the plant's ability to explore Al and Fe-bound nutrients (Table 3). In Dystrudept soil, differences in root biomass between treatments were relatively small and mostly non-significant, although S_2T_4 showed a trend of increase. This indicates that in soils with coarser textures and low nutrient binding capacity, root response to fertilizer application is more limited by soil physical factors.

Shoot biomass showed a consistent pattern with total biomass. Treatments S_1T_4 (59.40 g) and S_1T_3 (54.21 g) produced the highest shoot biomass and were significantly different from the control. This increase reflects increased photosynthetic efficiency and sustained nutrient supply due to the combination of nanocompost and NPK. In Dystrudept, despite lower shoot biomass, S_2T_4 (39.02 g) still showed a significant difference compared to the control. This confirms that nanocompost plays a role in maintaining nutrient availability in the root zone, thus supporting shoot growth even under unfavorable soil conditions. The non-significant shoot/root ratio across treatments indicates balanced biomass allocation (Table 3), suggesting that nanocompost enhances growth without altering root–shoot proportionality, an important indicator of seedling quality.

The enhanced biomass accumulation under nanocompost-based treatments is closely associated with improved cation exchange capacity (CEC) and nutrient retention. Nanoparticle-enriched nanocompost increases active exchange sites and stabilizes nutrient availability in the root zone, reducing leaching losses and improving fertilizer-use efficiency. The non-significant shoot/root ratio indicates balanced biomass allocation driven by improved nutrient availability rather than altered growth partitioning. In Hapludult, the nano-compost treatments (T_2–T_4) produced markedly higher biomass and chlorophyll indices (SPAD value), suggesting improved nutrient retention and availability. Conversely, Dystrudept characterized by low organic matter and poor nutrient-holding capacity (Table 1) showed smaller relative increases, though still significantly moisture retention, where the nanoparticles can effectively adsorb and release nutrients in synchrony with root uptake.

Table 3 Effect of soil type and fertilizer treatments on total dry weight of biomass, dry weight of shoot, dry weight of root and shoot/root ratio of oil palm seedlings after 7 months

Soil type	Fertilization	Total dry weight of plant (g)	Dry weight of shoot (g)	Dry weight of roots (g)	Shoo/root ratio
Hapludult (S1)	T0 (control)	33.61±4.83^{ab}	25.67±3.74^{ab}	7.94±1.61^{ab}	3.28±0.46
	T1 (100% NPK)	58.82±9.10^{c}	47.92±9.16d^{ef}	10.91±1.58^{b}	4.50±1.28
	T2 (100% NEN)	56.95±10.33^{c}	44.90±9.84^{cde}	12.05±2.37^{bc}	3.83±1.02
	T3 (50% NPK+50% NEN)	70.12±8.84^{cd}	54.21±8.23^{ef}	15.91±3.44^{c}	3.54±0.95
	T4 (25% NPK+75% NEN)	74.66±17.08d	59.40±13.39^{f}	15.26±4.13^{bc}	3.96±0.65
Dystrudept (S2)	T0 (control)	22.50±1.61^{a}	18.37±1.25^{a}	4.13±0.45^{a}	4.47±0.34
	T1 (100% NPK)	30.26±5.76^{ab}	25.07±4.39^{ab}	5.19±1.52^{a}	4.95±0.66
	T2 (100% NEN)	39.70±9.21^{b}	33.54±8.40^{bc}	6.16±1.10^{a}	5.46±0.93
	T3 (50% NPK+50% NEN)	35.62±5.53^{ab}	30.03±4.42^{abc}	5.60±1.36^{a}	5.55±1.12
	T4 (25% NPK+75% NEN)	47.63±10.30^{bc}	39.02±10.11^{cd}	8.61±1.40^{ab}	4.62±1.43
HSD 5%		14.37	12.07	4.49	ns

Values followed by different letters within the same columns differ significantly at $p < 0.05$ (Tukey's HSD).

Discussion

In comparison to control and sole inorganic fertilizer treatments, the current study shows that the incorporation of nano-compost enriched with ZnO and SiO_2 nanoparticles greatly enhanced the nursery growth performance of oil palm seedlings. The efficiency of nano-based organic additions is influenced by natural soil fertility, as demonstrated by the significant role that soil type played in modifying responses. Consistent with recent findings in agro-nanotechnology, nanoparticle-enhanced fertilizers offer improved nutrient delivery and efficiency relative to conventional inputs. Nano-fertilizers such as metal oxide nanoparticles, including ZnO and SiO_2, exhibit controlled release properties, enhanced reactivity, and targeted nutrient availability, which reduce leaching losses and improve crop uptake efficiency which are key drivers of improved growth and nutrient use efficiency observed in this study. This aligns with broader evidence that nano-fertilizers can enhance plant growth, nutrient uptake, and physiological performance while potentially lowering environmental impacts compared to conventional fertilization strategies (Mridha et al., 2025).

When compared to Dystrudept, oil palm seedlings grown on Hapludult soil consistently shown better vegetative development, including plant height, stem diameter, and leaf area. The different responses between Hapludult and Dystrudept confirm that soil physicochemical properties govern nanocompost efficiency. In highly weathered Dystrudept, the nanocompost compensated for nutrient leaching by forming stable nano-aggregates that retained ions longer within the root zone. Similar mechanisms have been reported by Rahman et al. (2018) in their study reported that oil-palm soil fertility dynamics were influenced by the organic matter content of the soil. Nano-sized composites rich in organic matter (OM) and poorly-crystalline minerals enhance the stability of soil aggregates (Asano et al., 2018). The addition of nano-compost promotes microbial diversity, which is crucial for the formation of microaggregates. These aggregates protect soil organic carbon (SOC) and enhance nutrient cycling (Arachchige et al., 2024).

These findings are consistent with the previous reports that nano-added compost can increase soil aggregation, microbial biomass, and nutrient use efficiency (Asmawi et al., 2024). The integration of nanoparticles into compost has been demonstrated to significantly augment soil structure, enhance nutrient availability, water retention, and microbial activity, all of which are essential for maintaining soil health. The incorporation of these substances not only prolongs the mean residence time of organic matter but also improves the overall chemical characteristics of the soil, resulting in enhanced plant growth and productivity (Medina et al., 2021; Rout & Aggarwal, 2024). Abdullatif et al. (2024) reported that organic nanoparticles (CNPs) significantly influence soil organic carbon (SOC) change, enhancing soil structure and aggregation, particularly in sandy and clay soils low in organic matter, thereby improving soil resistance to degradation and promoting carbon sequestration. The presence of nanoparticles can lead to the formation of nanoaggregates, which are essential for improving soil reactivity and nutrient transport, soil's water retention capacity and nutrient availability, which are vital for plant growth and soil health (Perdrial et al., 2010; Bayat et al., 2018; Rahmati & Kousehlou, 2023). Improved soil conditions have a positive effect on plant growth. The synergistic response observed in the combined treatment (T_3) suggests that partial substitution of chemical fertilizer with nanocompost optimizes both nutrient supply and soil health.

While nutrient limitation in Dystrudept limited seedling growth, this pattern shows enhanced nutrient retention and cation exchange capacity inherent in Hapludult, facilitating higher nutrient availability and utilization when paired with nano-compost. Therefore, the amount of seedling response to amendments is determined by the physicochemical features of the soil, which emphasizes the significance of matching nano-fertilizer techniques with intrinsic soil fertility. Dystrudept soil has a lower soil fertility level than Hapludult (Table 1), so it requires a higher dose of soil conditioner to improve nutrient availability. The results of this study are in line with those reported by Navarrete et al. (2013); Galgo & Asio (2022) that these soils frequently have low CEC, which restricts their capacity to hold onto vital elements including calcium (Ca), magnesium (Mg), and potassium (K) (Piamonte et al., 2014; Osman, 2018; Mulyadi & Arruan, 2019).

Treatments combining nano-compost with reduced NPK (e.g., 50% NPK + 50% NEN) consistently achieved equal or superior growth compared with full inorganic fertilizer application. This likely results from synergistic interactions between the organic matter in compost, which improves soil moisture and microbial activity, and the nano-particles' enhancement of nutrient availability and uptake. Nanoparticles increase surface area and reactive sites within the organic matrix, enhancing nutrient adsorption and slow release, thereby improving fertilization efficiency while reducing the need for high doses of mineral fertilizers, a key objective of sustainable nursery practices. ZnO nanoparticles specifically have been shown to enhance chlorophyll synthesis, photosynthetic activity, and stress resilience, owing to Zn's integral role in enzyme catalysis and metabolite synthesis in plant systems, leading to enhanced overall plant health. Research indicates that application of ZnO-NPs at concentration 100 mgL^{-1} improves chlorophyll content, photosynthetic efficiency, and growth parameters across various plant species, including maize, tea, barley, and tomato (Faizan et al., 2018; Ahmad et al., 2022; Chen et al., 2024). Meanwhile, SiO_2 nanoparticles can promote structural development and improve abiotic stress tolerance by strengthening cell walls and regulating water relations. The presence of SiO_2 NPs has been linked to increased chlorophyll content and photosynthetic efficiency, which are crucial for plant growth under abiotic stress (Sun et al, 2023; Daler et al., 2024; Kumar, 2024; Cao et al., 2025).

Significant interactions between soil type and fertilization were observed for nutrient uptake and SPAD chlorophyll values. The result of this study showed that 100% NPK produced the highest absolute uptake on nutrient-poor soils. Conventional NPK fertilizers can lead to quick improvements in crop performance, especially in nutrient-deficient soils (Guillén-Castillo et al., 2023; Jithendar et al., 2024). However, combined treatments (50% NPK + 50% NEN) yielded comparable nutrient uptake and SPAD indices, particularly in the more fertile soil. Nanocompost provides a slow-release source of nutrients and organic matter, while NPK ensures immediate nutrient availability. These fertilizers improve nutrient retention in the soil, leading to better absorption by plants and increased crop yields (Kráľová & Jampílek, 2023; Singh et al., 2024). This dual effect enhances photosynthetic activity (as reflected by higher SPAD values) and root growth, aligning with previous findings that nanocomposts improve nutrient-use efficiency and microbial functioning (Haydar et al., 2024; Sales et al., 2024).This suggests that nano-compost can maintain or enhance physiological performance while reducing reliance on synthetic fertilizers, consistent with literature stating that nano-based fertilizers can increase nutrient efficiency and support physiological processes including photosynthesis and antioxidant defense responses (Nazeer et al., 2023; Babu et al., 2024).

In terms of biomass accumulation, nano-compost treatments promoted balanced shoot and root growth, with higher total and root biomass compared to control or sole inorganic treatments. Increased root proliferation enhances soil exploration and nutrient acquisition, critical for seedlings transitioning to field conditions. Maintaining a consistent shoot-to-root ratio indicates that these treatments did not disrupt biomass partitioning a positive indicator for seedling vigor. Overall, the results suggest that nano-compost enriched with ZnO and SiO_2 nanoparticles can improve seedling quality under nursery conditions by enhancing nutrient use efficiency, physiological performance, and biomass accumulation even when inorganic fertilizer inputs are reduced. These benefits support broader trends in sustainable agriculture that integrate nano-fertilizers to improve crop performance, reduce environmental impacts, and enhance resource use efficiency (Thangavelu et al., 2024). Importantly, however, future studies should further evaluate long-term ecological impacts, soil microbial interactions, and field performance to ensure safe and scalable applications of nanotechnologies in perennial crop systems (Mridha et al., 2025).

Conclusion and recommendation

This study demonstrated that the application of nanoparticle-enriched nanocompost derived from oil palm waste (EFB + solid decanter) significantly enhanced the growth and physiological performance of *Elaeis guineensis* seedlings in the main nursery stage. Growth parameters such as plant height, stem diameter, number of leaf sheaths, leaf area, length of leaf sheath, biomass, and chlorophyll index were markedly improved under nanocompost treatments, particularly in combination with NPK fertilizer. Among the tested treatments, T4 (25% NPK + 75% NEN) produced the most favorable results, indicating a strong synergistic effect between organic-nano amendments and inorganic fertilizers. Overall, the findings recommend that integrating nano-compost with conventional fertilization can optimize nutrient-use efficiency while reducing chemical fertilizer dependency contributing to sustainable oil-palm nursery management and environmental protection. Further research should focus on (1) long-term field trials to assess nutrient release kinetics and yield response under plantation conditions (2) nanoparticle characterization in soil plant interfaces and (3) evaluation of microbial dynamics and nutrient cycling influenced by nano-organic interactions.

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Data availability: The data is available from the authors upon reasonable request and included within the article or its supplementary materials.

Declarations

i. Ethics approval and consent to participate: Ethical approval for this study was obtained from all individual participants included in the study

ii. Conflict of Interest: The authors declare no conflict of interest.

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