Agricultural Revolution Journal
https://ejournal.cibnusantara.org/agrivolution
E- ISSN: 3108-9062

Interactive Effects of Volcanic Ash and Cow Manure on the Growth of Oil Palm Seedlings in Ultisol During the Main Nursery Stage

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Article history:
Received: March 2nd, 2026
Accepted: April 29th, 2026
Published: May 15th, 2026

DOI:
https://doi.org/10.64570/agrivolution.v2i1.57

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Abstract: Producing vigorous oil palm (*Elaeis guineensis* Jacq.) seedlings in the main nursery is essential for field establishment, yet Ultisols, widely used as nursery media, are acidic and low in fertility and organic matter. Volcanic ash is a mineral amendment whose nutrients are released slowly, whereas cow manure supplies organic matter and nutrients that may accelerate its weathering. This study evaluated the interactive effects of volcanic ash and cow manure on the vegetative growth of oil palm seedlings in Ultisol during the main nursery stage. A factorial experiment in a Completely Randomized Design combined three volcanic ash rates (75, 150, and 225 g polybag^{-1}) with four cow manure rates (375, 750, 1,125, and 1,500 g polybag^{-1}), giving 12 treatment combinations with three replications. Seedling height, stem diameter, number of fronds, and leaf area were recorded at 18 weeks after transplanting and analyzed by two-way ANOVA followed by Duncan's Multiple Range Test ($P \leq 0.05$). Significant interactions were found for seedling height and stem diameter. The tallest seedlings (99.67 cm) occurred with 225 g volcanic ash and 1,500 g cow manure, while the thickest stems (48.00 mm) occurred with 225 g volcanic ash combined with 1,125–1,500 g cow manure. Number of fronds (12.28) and leaf area (3,361.44 cm^2) responded only to cow manure, peaking at 1,500 g polybag^{-1}. These results indicate that volcanic ash and cow manure act synergistically to promote stem elongation and thickening, whereas leaf development depends on the supply of organic nutrients.

Keywords: cow manure, nursery media, soil amendment, volcanic ash.

1. INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is one of the most economically important plantation crops worldwide, providing the largest share of global vegetable oil production. Indonesia remains the leading producer of crude palm oil, with plantation areas exceeding 15 million hectares and continuing to expand annually. This rapid expansion increases demand for high-quality planting materials that ensure optimal field establishment and long-term productivity. Consequently, successful nursery management has become one of the most critical stages in oil palm cultivation because seedling quality strongly determines subsequent plantation performance (Badan Pusat Statistik, 2024).

The main nursery stage represents the most important phase of seedling development, during which vigorous vegetative growth is required before seedlings are transplanted to the field. Seedlings with greater plant height, larger stem diameter, and well-developed

foliage generally exhibit better adaptability after transplanting and produce higher survival rates under field conditions (Akenda, 2021).

In Indonesia, Ultisols are widely used as nursery growing media due to their extensive distribution (Hardiyanti et al., 2025). However, these soils are characterized by low fertility, acidic pH, low organic matter content, and poor nutrient availability, all of which restrict root development and vegetative growth (Abadi & Nelvia, 2018; Aminullah et al., 2017). Improving the physical and chemical properties of Ultisols is therefore necessary to enhance nutrient uptake and optimize seedling growth.

Among various soil amendments, volcanic ash has attracted increasing attention due to its abundance after volcanic eruptions and its potential as a natural mineral resource. Volcanic ash contains numerous macro- and micronutrients, including phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), which contribute to soil fertility improvement (Barus et al., 2021). Previous studies have demonstrated that volcanic ash may increase soil pH, improve cation exchange capacity, enhance phosphorus retention, and improve soil physical properties through its porous structure (Fiantis et al., 2010; Sefano & Gusmini, 2024; Yuliana et al., 2017). In oil palm seedlings, the application of volcanic ash has been reported to increase seedling height and stem diameter, indicating its potential as an alternative soil amendment for nursery media (Alviandy et al., 2016).

Despite these advantages, freshly deposited volcanic ash cannot immediately function as an effective nutrient source because most minerals remain in relatively unavailable forms. Newly erupted volcanic materials require weathering before nutrients become accessible for plant uptake (Nurlaeny et al., 2012). Consequently, strategies that accelerate mineral weathering are required to maximize the agronomic value of volcanic ash.

Organic amendments are considered effective in accelerating mineral weathering because they release humic substances and organic acids during decomposition. These compounds enhance mineral dissolution, stimulate microbial activity, and increase nutrient availability within the rhizosphere (Damayani et al., 2014). Cow manure is particularly suitable because it provides organic matter and essential nutrients while also improving soil aggregation, water retention, microbial activity, and cation exchange capacity (Nurlina et al., 2018; Wicaksono et al., 2015). In addition, cow manure provides substantial amounts of nitrogen, phosphorus, potassium, calcium, magnesium, and organic carbon that support vegetative growth. Previous studies have shown that cow manure significantly increases plant height, stem diameter, leaf area, and biomass accumulation of oil palm seedlings grown under nursery conditions (Rizki et al., 2024).

The simultaneous application of volcanic ash and cow manure offers a promising strategy to improve Ultisol fertility, as the two materials may complement each other. While volcanic ash supplies long-term mineral nutrients, organic matter from cow manure accelerates weathering processes, enhances microbial activity, and facilitates nutrient release. Previous studies have suggested that combining volcanic materials with organic amendments may improve soil physical, chemical, and biological properties more effectively than either material applied alone (Nurlaeny et al., 2012; Narka et al., 2021). In

plantation-crop seedlings, a significant interaction between volcanic ash and goat manure on seedling height, shoot dry weight, and root-to-shoot ratio has also been reported for Robusta coffee (Novio et al., 2026). However, information regarding the interactive effects of volcanic ash and cow manure on vegetative growth of oil palm seedlings during the main nursery stage remains limited, particularly under Ultisol conditions.

Most previous studies have evaluated either volcanic ash or organic manure in isolation, whereas quantitative evidence on their interaction and optimal combination for oil palm nursery production remains scarce. Understanding these interactions is essential because synergistic responses between mineral and organic amendments may substantially improve seedling performance while reducing dependence on synthetic fertilizers.

Therefore, this study aimed to evaluate the interactive effects of volcanic ash and cow manure on vegetative growth of oil palm seedlings grown in Ultisol during the main nursery stage. Specifically, this study investigated their effects on seedling height, stem diameter, leaf production, and leaf area to identify the most effective combination for improving nursery media and promoting vigorous seedling growth.

2. METHOD

The experiment was conducted from January to July 2025 at the Experimental Field and Soil Fertility Laboratory, Department of Plantation Crop Cultivation, Faculty of Agriculture, Universitas Andalas, Campus III Dharmasraya, West Sumatra, Indonesia. The study evaluated the effectiveness of volcanic ash and cow manure as amendments to the growing media for oil palm seedlings cultivated in Ultisol during the main nursery stage.

Four-month-old oil palm (*Elaeis guineensis* Jacq.) seedlings of the DxP 540 NG variety were used as planting materials. Uniform seedlings with an average height of approximately 25 cm, four fully expanded leaves, healthy green foliage, and free from visible pest and disease symptoms were selected prior to transplanting.

The growing medium consisted of Ultisol collected from the topsoil layer (0–20 cm). The soil was air-dried, cleaned of roots, stones, and other debris, and sieved through a 2-mm mesh before use. Volcanic ash used in this study originated from the eruption of Mount Marapi in West Sumatra, Indonesia, on 3 December 2023. The ash had naturally weathered for approximately one year before application. Samples were collected from Andaleh Village, Tanah Datar Regency, West Sumatra, using a composite sampling procedure from four to five collection points within an area of approximately 5 m^2. Cow manure was obtained from a local cattle farm and had undergone composting prior to use.

The initial chemical properties of the Ultisol, volcanic ash, and cow manure were analyzed prior to the application of the treatments. Soil analysis included pH, total nitrogen, available phosphorus, exchangeable potassium, and organic carbon. Volcanic ash was analyzed for pH, phosphorus, potassium, moisture content, and particle fineness. In contrast, cow manure was analyzed for pH, total nitrogen, phosphorus, potassium, organic carbon, moisture content, and C/N ratio following the analytical procedures described by Eviati et al. (2023).

Experimental Design

The experiment was arranged as a two-factor factorial in a Completely Randomized Design (CRD). The first factor was volcanic ash applied at three rates: 75 g polybag^{-1} (V_1, equivalent to 15 t ha^{-1}), 150 g polybag^{-1} (V_2, 30 t ha^{-1}), and 225 g polybag^{-1} (V_3, 45 t ha^{-1}). The second factor was cow manure applied at four rates: 375 g polybag^{-1} (M_1, equivalent to 75 t ha^{-1}), 750 g polybag^{-1} (M_2, 150 t ha^{-1}), 1,125 g polybag^{-1} (M_3, 225 t ha^{-1}), and 1,500 g polybag^{-1} (M_4, 300 t ha^{-1}). Combining the two factors yielded 12 treatment combinations, each replicated 3 times, for a total of 36 experimental units.

Seedlings were grown under approximately 30% shade using shade nets throughout the experiment. Irrigation was performed twice daily, in the morning and afternoon, to maintain adequate soil moisture. Weeds were manually removed whenever necessary. Preventive pest and disease management was carried out using deltamethrin (25 g L^{-1} active ingredient) applied at a concentration of 2 mL L^{-1} water once every week throughout the nursery period.

Vegetative Growth Measurements

Vegetative growth was evaluated using four agronomic parameters. Plant height (cm) was measured every two weeks from two weeks after transplanting until 18 weeks after transplanting (WAT). Measurements were taken from the root collar to the tip of the highest fully extended leaf using a ruler. Stem diameter (mm) was determined every two weeks using a digital caliper at approximately 2 cm above the soil surface. The number of fully expanded leaves was recorded every two weeks by counting all leaves that were fully unfolded. Leaf area (cm²) was measured at the end of the experiment (18 WAT) using the gravimetric method. Individual leaf outlines were traced on paper of uniform thickness, cut according to the traced pattern, and weighed. Leaf area was calculated by comparing the weight of the paper replica to that of a standard paper area (10 × 10 cm), following the gravimetric procedure described by Eviati et al. (2023).

Statistical Analysis

Data were analyzed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). All variables were subjected to a two-way analysis of variance (ANOVA) appropriate for a factorial arrangement in a Completely Randomized Design (CRD) to determine the effects of volcanic ash, cow manure, and their interaction on the vegetative growth of oil palm seedlings. Whenever the ANOVA indicated significant treatment effects at the 5% probability level, treatment means were separated using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$.

3. RESULT AND DISCUSSION

1. Seedling Height (cm)

Analysis of variance revealed a significant interaction between volcanic ash and cow manure on the height of oil palm seedlings at 18 weeks after transplanting (WAT), indicating that the effectiveness of volcanic ash depended on the rate of cow manure application and vice versa. As presented in Table 1, seedling height consistently increased

with increasing cow manure application across all volcanic ash rates. However, the magnitude of this response became more pronounced as the volcanic ash rate increased. The combination of 225 g polybag^{-1} volcanic ash and 1,500 g polybag^{-1} cow manure produced the tallest seedlings (99.67 cm). In contrast, the lowest seedling height (86.67 cm) was recorded in seedlings receiving 75 g polybag^{-1} volcanic ash combined with 375 g polybag^{-1} cow manure. These results demonstrate a positive interaction between mineral and organic amendments in promoting vegetative growth of oil palm seedlings.

Table 1. Oil palm seedling height (cm), age 18 MST due to the application of volcanic ash and cow manure at different doses

Dose Abu Vulkanik (g/*polybag*)	Cow Manure (g/*polybag*)			
	375	750	1.125	1.500
75	86,67 b A	88,00 from B	89,33 a B	90,00 a B
150	88,00 b A	90,67 from FROM	91,00 a B	92,67 a B
225	88,67 b B	91,00 b FROM	98,00 a A	99,67 a A
KK = 2.6%				

Remarks: Numbers in the same column, followed by the same uppercase letter, and in the same row, followed by the same lowercase letter, indicate different intangibles based on the DMRT test at the 5% significance level.

The significant interaction suggests that volcanic ash alone was insufficient to maximize seedling growth, but its effectiveness increased substantially when combined with higher rates of cow manure. This complementary response indicates that the organic amendment likely enhanced the agronomic effectiveness of volcanic ash by improving nutrient availability and the properties of the growing medium. Organic matter supplied by cow manure may stimulate microbial activity and release organic acids during decomposition, thereby accelerating mineral weathering and facilitating nutrient release from volcanic ash (Damayani et al., 2014; Tarigan et al., 2017). Consequently, nutrients contained in volcanic ash become more available for plant uptake, resulting in greater vegetative growth than when either amendment functions independently.

The superior performance observed under the highest combined application can also be attributed to the complementary roles of the two amendments in improving Ultisol fertility. Volcanic ash contains considerable amounts of phosphorus, potassium, calcium, magnesium, and several micronutrients that contribute to improving soil fertility (Barus et al., 2021; Fiantis et al., 2010). Nevertheless, freshly weathered volcanic ash generally releases nutrients gradually because many mineral constituents remain in relatively unavailable forms (Nurlaeny et al., 2012). The addition of cow manure supplies readily available nutrients while simultaneously improving soil physical properties, increasing cation exchange capacity, enhancing soil aggregation, and promoting microbial activity (Nurlina et al., 2018; Wicaksono et al., 2015). These improvements create a more favorable

rhizosphere environment that enhances nutrient uptake efficiency and supports continuous seedling growth.

Among the nutrients supplied by volcanic ash, phosphorus and potassium are likely responsible for the increased seedling height observed in this study. Phosphorus plays an essential role in energy transfer, ATP synthesis, cell division, and meristematic development, whereas potassium regulates enzyme activation, osmotic adjustment, carbohydrate translocation, and photosynthetic efficiency (Hardjowigeno, 2013). Adequate availability of these nutrients promotes stem elongation and accelerates vegetative development of oil palm seedlings. Similar responses following volcanic ash application have been reported by Alviandy et al. (2016), who found significant improvements in seedling height associated with enhanced availability of essential mineral nutrients.

The positive response to cow manure application is also consistent with its role as an important source of organic matter and essential macronutrients. Cow manure used in this study contained nitrogen, phosphorus, and potassium, all of which are fundamental for vegetative growth. Nitrogen stimulates chlorophyll formation, protein synthesis, and cell division, thereby promoting stem elongation and leaf development, while phosphorus and potassium support root growth, energy metabolism, and assimilate translocation (Prasetya, 2014). The gradual increase in seedling height with increasing cow manure rates indicates that nutrient supply remained a limiting factor for seedling growth in Ultisol and that higher organic amendment rates effectively alleviated these limitations.

The absence of a growth plateau at the highest treatment combination further suggests that integrating volcanic ash and cow manure improved the growing medium beyond simple nutrient supplementation. Organic matter likely enhanced moisture retention and nutrient buffering capacity, while volcanic ash contributed mineral reserves that sustained plant growth throughout the nursery period. Such complementary functions explain the significant interaction detected by ANOVA and support the hypothesis that integrating mineral and organic amendments is more effective than applying either material alone.

2. Stem Diameter (mm)

Analysis of variance revealed a significant interaction between volcanic ash and cow manure on the stem diameter of oil palm seedlings grown in Ultisol during the main nursery stage. This finding indicates that the response of stem diameter to cow manure application depended on the rate at which volcanic ash was incorporated into the nursery medium. Such an interaction suggests that improvements in seedling stem growth resulted from the complementary functions of mineral and organic amendments rather than from the individual contributions of each material.

Stem diameter generally increased with increasing rates of cow manure across all volcanic ash treatments. The largest stem diameter (48.00 mm) was recorded in seedlings receiving 225 g polybag^{-1} volcanic ash combined with either 1,125 or 1,500 g polybag^{-1} cow manure (Table 2). However, these treatments did not differ significantly from the combination of 150 g polybag^{-1} volcanic ash and 1,500 g polybag^{-1} cow manure. Conversely, the smallest stem diameter was observed in seedlings treated with the lowest application rates of both

amendments. These results indicate that an adequate supply of organic nutrients was required to maximize the beneficial effect of volcanic ash on stem development.

Table 2. The diameter of the oil palm seedling stem (mm) is 18 MST due to the application of volcanic ash and cow manure at different doses.

Dose Abu Vulkanik (g/*polybag*)	Cow Manure (g/*polybag*)			
	375	750	1.125	1.500
75	41,67 b B	43,33 b B	46,00 a A	47,33 a A
150	41,67 b B	46,67 a A	47,33 a A	47,67 a A
225	47,67 a A	47,67 a A	48,00 a A	48,00 a A
KK= 3.7%				

Remarks: Numbers in the same column, followed by the same uppercase letter, and in the same row, followed by the same lowercase letter, indicate different intangibles based on the DMRT test at the 5% significance level.

The positive interaction between volcanic ash and cow manure may be attributed to their complementary roles in improving the physical and chemical properties of Ultisol. Volcanic ash is recognized as a potential mineral amendment that contains essential nutrients, particularly potassium, calcium, magnesium, and various micronutrients, which are gradually released through weathering processes. However, the availability of these nutrients is often limited during the early stages of application because nutrient release depends on mineral dissolution. In contrast, cow manure provides readily available nutrients while simultaneously increasing soil organic matter content, improving soil aggregation, enhancing water-holding capacity, and stimulating microbial activity. The decomposition of organic matter also produces organic acids that accelerate the weathering of volcanic ash minerals, thereby increasing nutrient availability for plant uptake. Consequently, integrating both amendments creates a more favorable root environment than applying either amendment individually.

Stem diameter is widely recognized as an important indicator of seedling vigor because it reflects the accumulation of structural biomass and the capacity of seedlings to support future vegetative growth after transplanting. Enlargement of stem diameter is closely associated with active cell division and cell enlargement within the vascular cambium, processes that require an adequate supply of nutrients, particularly phosphorus and potassium. Phosphorus plays a central role in energy transfer and cell division, whereas potassium regulates enzyme activation, carbohydrate translocation, osmotic balance, and the formation of structural tissues. Therefore, the improved availability of these nutrients in amended Ultisol likely promoted greater radial stem growth, resulting in thicker and more vigorous seedlings. Similar observations have been reported by Alviandy et al. (2016), who demonstrated that improved phosphorus availability significantly enhanced stem growth in oil palm seedlings. Likewise, Jatsiyah et al. (2020) reported that organic

amendments improved nutrient availability and promoted more vigorous vegetative growth through enhanced soil fertility. The application of volcanic ash has also been reported to affect the stem diameter of Robusta coffee seedlings (Novio et al., 2026).

The increasing response of stem diameter with higher cow manure application also highlights the importance of organic matter in ameliorating the inherent limitations of Ultisol. These soils are generally characterized by low organic carbon, low cation exchange capacity, high acidity, and limited nutrient availability, conditions that restrict root growth and nutrient absorption. The addition of cow manure improves these constraints by increasing nutrient retention and reducing nutrient losses through leaching, thereby ensuring a more continuous nutrient supply throughout seedling development. The gradual release of nutrients from volcanic ash complements this process by providing additional mineral nutrients that become increasingly available as weathering progresses. This complementary nutrient-release pattern explains why the interaction between volcanic ash and cow manure produced a greater stem diameter than either amendment applied separately.

Although increasing cow manure application consistently enhanced stem diameter, the results also suggest that the response tended to plateau at the highest amendment rates. Seedlings receiving 225 g polybag^{-1} volcanic ash combined with 1,125 g polybag^{-1} cow manure exhibited stem diameters comparable to those receiving 1,500 g polybag^{-1} cow manure, indicating that further increases in organic amendment provided only marginal additional benefits. This finding implies that an optimum balance between mineral and organic amendments is more important than maximizing the application rate of a single amendment.

3. Number of Fronds (strands)

Analysis of variance indicated that the interaction between volcanic ash and cow manure had no significant effect on the number of fronds produced by oil palm seedlings during the main nursery stage. Likewise, volcanic ash alone did not significantly influence frond production. In contrast, cow manure exerted a significant main effect, with the highest application rate (1,500 g polybag^{-1}) producing the greatest number of fronds (12.28 fronds per seedling), significantly exceeding the lower manure application rates (Table 3). These findings suggest that frond production was primarily determined by the availability of nutrients supplied by organic amendment rather than by interactions between mineral and organic amendments.

The absence of a significant interaction indicates that frond production responded to cow manure in a relatively consistent manner across all volcanic ash application rates. Similarly, the lack of a significant main effect of volcanic ash suggests that mineral nutrients released from the volcanic material were insufficient to alter the rate of leaf initiation within the duration of the nursery experiment. Although volcanic ash contains substantial amounts of phosphorus and potassium that are essential for plant growth, these nutrients are largely associated with primary minerals and require weathering before becoming available for plant uptake. Consequently, the beneficial effects of volcanic ash are more likely to become apparent over a longer period than the 18-week observation

period employed in this study. A lack of significant interaction between two soil amendments or fertilizer factors on seedling growth has likewise been reported for oil palm seedlings grown on ex-limestone mining soil and for sugar palm seedlings (Suhendra et al., 2024).

Table 3. The number of palm fronds aged 18 MST due to the application of different volcanic ash and cow manure

Dose Abu Vulkanik (g/*polybag*)	Cow Manure (g/*polybag*)				Influence Single Volcanic Ash
	375	750	1.125	1.500	
75	10,66	11,16	11,50	11.83	11,29
150	10,83	11.67	11,50	12,33	11,58
225	11,33	11,33	12,00	13,00	11,91
Single Effect of Cow Manure	11,33 b	11,39 b	11,78 b	12,28 a	
KK = 6.2%					

Remarks: Numbers on the same line and with the same lowercase letters indicate different intangibles, as determined by the DMRT test at a significance level of 5%.

The significant increase in fronds following cow manure application can be attributed to improved soil fertility and biological activity. Cow manure supplies essential nutrients, particularly nitrogen, phosphorus, and potassium, while simultaneously increasing soil organic matter and stimulating microbial activity. Enhanced microbial decomposition accelerates nutrient mineralization, thereby increasing nutrient availability in the rhizosphere and supporting continuous vegetative development. These processes provide a favorable environment for sustained leaf development in nursery-grown of oil palm.

Among the nutrients supplied by cow manure, nitrogen likely played the most important role in promoting frond production. Nitrogen is an essential component of chlorophyll, amino acids, proteins, and nucleic acids, making it indispensable for cell division and the development of new vegetative tissues. An adequate nitrogen supply enhances photosynthetic capacity, increases assimilate production, and supports the emergence of new leaves throughout the nursery period. The present findings agree with those of Lingga and Marsono (2013), who reported that sufficient nitrogen availability accelerates vegetative growth. Increased leaf formation ultimately enhances the photosynthetic surface available for biomass accumulation and seedling establishment.

The negligible response of fronds to volcanic ash application may also reflect the inherent developmental characteristics of oil palm seedlings. Unlike plant height and stem diameter, which responded positively to the combined amendments, leaf initiation in oil palm is strongly regulated by genetic and developmental factors. Oil palm typically produces only one to two new fronds per month during the nursery stage, resulting in relatively small treatment differences over short experimental periods. Consequently, improvements in soil fertility do not necessarily translate into immediate increases in

frond production, particularly when environmental conditions are already favorable for normal growth. Similar observations have been reported by Madusari (2020), who emphasized the dominant role of genetic factors in determining leaf production among oil palm genotypes, while Harahap (2018) noted that frond emergence follows a relatively constant developmental pattern regardless of moderate variations in nutrient availability.

4. Leaf Area (cm^2)

Analysis of variance indicated that the interaction between volcanic ash and cow manure had no significant effect on the leaf area of oil palm seedlings during the main nursery stage. Likewise, volcanic ash applied as a single factor did not significantly influence leaf expansion. In contrast, cow manure application significantly increased leaf area, indicating that leaf development was primarily governed by nutrient availability from organic amendments rather than by the mineral contribution of volcanic ash.

Table 4. Oil palm leaf area of 18 MST due to the application of different volcanic ash and cow manure

Dose Abu Vulkanik (g/*polybag*)	Cow Manure (g/*polybag*)				Influence Single Volcanic Ash
	375	750	1.125	1.500	
75	2.183,67	2.629,33	1.839,67	3.430,67	2.520,84
150	1.409,33	2.326,67	3.321,67	3.503,33	2.640,25
225	2.309,33	2.597,67	2.985,67	3.150,33	2.760,75
Single Influence Cow Manure	1.967,44 c	2.517,89 b	2.715,67 b	3.361,44 a	
KK = 8.7%					

Remarks: Numbers on the same line and with the same lowercase letters indicate different intangibles, as determined by the DMRT test at a significance level of 5%.

Across all levels of volcanic ash application, leaf area increased progressively with increasing rates of cow manure. The largest leaf area was consistently obtained from seedlings receiving 1,500 g $polybag^{-1}$ of cow manure, whereas the lowest values were recorded in seedlings supplied with 375 g $polybag^{-1}$. This trend suggests that improving the organic matter content of Ultisol provided a more favorable environment for leaf expansion than increasing the rate of volcanic ash alone. The absence of a significant interaction further indicates that the beneficial effect of cow manure on leaf growth was relatively consistent regardless of the amount of volcanic ash incorporated into the nursery medium.

Leaf area is one of the most important indicators of vegetative performance because it determines the photosynthetically active surface available for light interception and carbon assimilation. An increase in leaf area generally reflects improved physiological performance and greater biomass production during the nursery stage. In the present study, the positive response to cow manure application was most likely associated with enhanced nutrient availability, particularly nitrogen, phosphorus, and potassium, together with improvements in the physical and biological properties of Ultisol. Organic matter

supplied by cow manure can improve soil aggregation, increase water-holding capacity, and enhance microbial activity, thereby creating a more favorable rhizosphere for nutrient uptake. These improvements ultimately promote leaf expansion and increase the photosynthetic capacity of oil palm seedlings (Jatsiyah et al., 2020).

The insignificant response of leaf area to volcanic ash application alone may be attributed to the relatively slow weathering rate of volcanic materials. Although volcanic ash contains considerable amounts of essential mineral nutrients, many of these nutrients remain in relatively insoluble forms and require longer periods of weathering before becoming available for plant uptake. Consequently, within the relatively short duration of the nursery experiment, volcanic ash primarily functioned as a soil amendment rather than as an immediately available nutrient source. Similar observations have been reported by Alviandy et al. (2016), who noted that volcanic ash generally exhibits gradual nutrient release, resulting in delayed responses in plant growth compared with readily decomposable organic amendments.

Unlike stem height and stem diameter, which exhibited significant interaction effects between volcanic ash and cow manure, leaf area responded predominantly to the main effect of cow manure. This difference suggests that leaf expansion was more dependent on the direct supply of readily available nutrients than on the synergistic improvement of soil chemical properties resulting from the combined application of mineral and organic amendments. Nitrogen supplied through cow manure plays a fundamental role in chlorophyll synthesis and protein formation, thereby stimulating leaf initiation and expansion, whereas phosphorus and potassium support cell division, carbohydrate translocation, and stomatal regulation during leaf development (Darmawan et al., 2020).

The absence of interaction also indicates that leaf expansion may be a relatively conservative growth parameter during the nursery stage. Compared with stem elongation and stem thickening, which rapidly respond to improvements in nutrient availability and root activity, leaf area development is influenced by genetic characteristics and developmental stage. Consequently, the contribution of volcanic ash to leaf expansion may require a longer cultivation period before its effects become physiologically apparent.

5. Agronomic Implications

The present study demonstrates that integrating volcanic ash with cow manure provides a practical and sustainable approach to improving oil palm seedling production in Ultisol-based nursery media. Ultisols are widely recognized for their low fertility, high acidity, and poor nutrient retention, which often limit seedling growth and increase dependence on inorganic fertilizers. The combined application of mineral and organic amendments offers an alternative strategy to overcome these constraints and improve nutrient utilization efficiency during the nursery stage.

The significant interaction observed for seedling height and stem diameter indicates that volcanic ash and cow manure complement each other in enhancing seedling growth. While cow manure supplies readily available nutrients and organic matter that stimulate early plant development, volcanic ash contributes essential mineral elements and

gradually improves the physicochemical properties of the growing medium. This complementary mechanism creates a more favorable environment for root activity and nutrient uptake, resulting in more vigorous vegetative growth than either amendment applied individually.

From a nursery management perspective, the application of 225 g polybag^{-1} volcanic ash combined with 1,500 g polybag^{-1} cow manure produced the most favorable vegetative growth and therefore represents the most suitable treatment among those evaluated. The use of locally available volcanic ash, together with livestock manure, may reduce dependence on synthetic soil amendments while improving the quality of nursery media. Such an approach is particularly relevant in regions where volcanic deposits and cattle manure are abundant but remain underutilized.

The findings also support the concept of integrated soil amendment management, in which mineral and organic materials perform complementary rather than substitutive functions. Organic amendments improve soil biological activity, aggregation, moisture retention, and nutrient availability, whereas volcanic ash serves as a long-term mineral source that sustains soil fertility through gradual weathering. Consequently, combining both materials not only enhances immediate seedling performance but also contributes to the development of healthier nursery media that support subsequent plant growth (Alviandy et al., 2016; Jatsiyah et al., 2020).

Beyond the nursery stage, vigorous seedlings with greater plant height, larger stem diameter, and improved leaf development are generally expected to exhibit better establishment following field transplantation. Although this study did not evaluate post-transplant performance, improved vegetative vigor during nursery development is widely regarded as an important indicator of seedling quality and early adaptation under field conditions (Darmawan et al., 2020).

4. CONCLUSIONS

Combining volcanic ash and cow manure improved the vegetative growth of oil palm seedlings in Ultisol during the main nursery stage. The two amendments had significant interactions on seedling height and stem diameter, indicating a synergistic effect, likely through complementary improvements in nutrient availability and growing media quality. In contrast, frond number and leaf area responded mainly to cow manure, suggesting that organic nutrient supply matters more than volcanic ash for leaf development under these conditions.

Among the combinations tested, 225 g polybag^{-1} volcanic ash with 1,500 g polybag^{-1} cow manure gave the most vigorous growth and is recommended for Ultisol-based nursery media. Using locally available volcanic ash together with manure is therefore a promising and sustainable way to overcome fertility constraints in Ultisols and improve nursery performance. Future research should examine the long-term effects on nutrient dynamics and soil biological activity, as well as seedling performance after field transplanting, to clarify the mechanisms behind the synergy.

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