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Effect of Soil Aggregate Size and Organic Matter on Tomato Early Growth, Yield and Root and Soil Physicochemical Properties

Uswah Hasanah*, Danang Widjajanto, Rezi Amelia, Abdul Rahman, Adrianton

Department of Agrotechnology, Faculty of Agriculture, Tadulako University, Palu 94118, Indonesia

Corresponding Author Email: uswahhasanah@untad.ac.id

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ABSTRACT

This study investigates the independent and combined effects of soil aggregate size (A1: <2 mm, A2: 2–4 mm, A3: >4–8 mm) and organic matter (OM) on tomato growth and soil properties. A pot experiment with a completely randomized design evaluated six treatments (a1b0, a1b1, a2b0, a2b1, a3b0, a3b1), where B1 represents the addition of 10% cow manure compost by soil dry weight, while B0 indicates no compost addition. Results demonstrated that OM alone significantly enhanced early root growth, plant height (79 cm vs. 44.6 cm without OM), leaf count (161 vs. 47 leaves), and fruit yield, which increased by a factor of 39 compared to non-OM treatments. Larger aggregates (>4–8 mm) significantly reduced soil bulk density (0.84 vs. 1.22 g cm^{-3} in A1) and increased available phosphorus by 30–40%. Interactions between OM and aggregate size significantly influenced tomato yield, total soil nitrogen, and hydraulic conductivity. The combination of large aggregates and OM (a3b1) boosted total nitrogen by 200–300% and fruit yield by 39 times compared to a1b0. While OM primarily enhanced root vigor and nutrient availability, aggregate size modulated phosphorus accessibility and physical soil structure. These findings underscore OM's dominant role in improving productivity and soil fertility, while aggregate size plays a crucial role in optimizing soil structure. Strategic integration of OM and aggregate management can enhance sustainable agricultural practices by balancing soil health and crop performance.

1. INTRODUCTION

Soil structure, a critical determinant of root development and nutrient uptake, is strongly governed by the spatial organization of soil particles into aggregates. These aggregates, formed through biotic and abiotic processes, govern soil porosity, hydraulic conductivity, and mechanical resistance, which in turn influence root architecture and overall plant productivity [1, 2]. While the role of soil aggregation in plant growth has been widely studied, the interactions between aggregate size and organic matter (OM) have not been extensively examined, particularly in the context of horticultural crops such as tomato (*Solanum lycopersicum* L.). This study addresses this gap by investigating how aggregate size and OM synergistically influence tomato growth, yield, and soil physicochemical properties—a critical step toward optimizing sustainable agricultural practices.

Aggregate size directly influences soil physical properties, such as bulk density and pore distribution, which in turn affect root penetration and resource acquisition. Smaller aggregates tend to form densely packed soils with reduced macropores, which increases mechanical impedance and restricts root elongation [3, 4]. Conversely, larger aggregates create a well-developed pore network that enhances aeration and water infiltration but may reduce root-soil contact efficiency in excessively coarse textures [5]. For instance, Lal [6] observed that medium-sized aggregates (2–4 mm) promoted superior early vegetative growth in tomatoes compared to finer or coarser fractions, though the long-term implications for yield remained unclear. Such findings highlight the need to evaluate aggregate size effects across plant developmental stages, particularly when combined with soil amendments like OM.

Organic matter is a key determinant of soil fertility, enhancing nutrient availability, microbial activity, and aggregate stability [7, 8]. By acting as a binding agent, OM fosters the formation of stable aggregates, reducing bulk density and enhancing porosity [9]. Additionally, OM decomposition releases plant-available nutrients, such as nitrogen and phosphorus, while stimulating microbial communities that further mineralize organic compounds [10]. For example, composted cow manure—rich in organic carbon and nitrogen—has been shown to elevate soil fertility in degraded soils [11]. However, the extent to which OM interacts with aggregate size to influence root-soil dynamics and crop performance remains poorly understood.

Previous studies have primarily focused on aggregate size and OM in isolation, overlooking their potential synergies or trade-offs. For instance, while OM consistently enhances nutrient availability, its efficacy may depend on aggregate-driven pore structures that regulate microbial habitats and nutrient diffusion [12, 13]. Similarly, larger aggregates may amplify OM's benefits by stabilizing macropores and reducing compaction, yet such interactions are rarely quantified. This knowledge gap limits our ability to design soil management strategies that balance structural and fertility improvements.

This study systematically evaluates the individual and interactive effects of three aggregate sizes (<2 mm, 2–4 mm, >4–8 mm) and OM (10% cow manure compost, based on soil dry weight) on tomato growth and soil properties. We hypothesize that (1) OM will dominantly enhance root vigor, nutrient uptake, and yield by mitigating soil physical limitations, and (2) Larger aggregates will optimize hydraulic conductivity and phosphorus availability, synergizing with OM to maximize productivity. By analyzing root morphology, vegetative growth, fruit yield, and key soil parameters (bulk density, nitrogen, phosphorus, hydraulic conductivity), this work provides mechanistic insights into how OM and aggregate size jointly shape soil-plant interactions.

The experiment utilized a low-fertility loam soil (pH 5.95, 1.17% C-organic) amended with OM to simulate realistic field conditions. Tomato, a globally significant crop with high nutrient demands, serves as an ideal model to assess agronomic outcomes. Results from this study will inform strategies for enhancing soil health and crop productivity in regions grappling with soil degradation, offering a template for sustainable intensification through integrated organic and structural management.

2. METHODOLOGY

2.1 Preparation of growth media

This study was conducted as a pot experiment in the Greenhouse of the Faculty of Agriculture at Tadulako University. The growing medium consisted of soil collected from Oti Village in the Sindue Tobata Subdistrict, Donggala Regency, Indonesia. The soils were air-dried (14 days) and sieved using three-layer sieves with openings of 2 mm, 4 mm, and 8 mm to retrieve various aggregate size fractions. The organic amendment is mainly comprised of composted cow dung collected from cattle pens located within the same area as the soil sampling site. The composting process involved homogenizing cow dung with husks, bran, sugar, water, and EM4 solution. This mixture was transferred to lidded containers at a depth of 15–20 cm and fermented for 14 days at 40–50℃. The resulting blackish organic material (10% of the soil's dry weight) was then blended with the sieved experimental soil media and placed into pots with a capacity of 7 kg of soil.

The soil was moistened to reach field capacity, covered with plastic, and then left for one week. The field capacity was approached by using a soil sample placed in stainless steel rings with 5 cm in diameter and 5 cm in height and were soaking for 24 hours until they were saturated. The soils then were carefully drained for two hours until no more water dripped at the base of the ring.

2.2 Planting and soil maintenances

The moistened soil, after being left for one week, was planted with three tomato seeds per pot. After one week, the plants were thinned to leave the best single plant. Pest and disease control was performed as symptoms of infestation were observed.

2.3 Experimental design

The experiment was arranged in a completely randomized design with two factors: soil aggregate size and organic matter. The soil aggregate sizes were classified into three levels: <2 mm aggregates (A1), 2–4 mm aggregates (A2), and >4–8 mm aggregates (A3). The organic matter factor had two levels: without organic matter (B0) and with 10% organic matter by soil mass (B1). This resulted in six treatment combinations: a1b0, a1b1, a2b0, a2b1, a3b0, and a3b1, with six replications for each treatment. One series of pots was used for root observations, and five series were used for plant and soil observations at harvest, resulting in a total of 36 experimental units.

2.4 Plant and soil observations

The plant observations included (i) visual assessment of root development during the early growth phase, (ii) plant height (using a standard rigid meter), (iii) number of leaves (by counting fully expanded true leaves), and (iv) fresh tomato fruit weight. The soil observations included the following: (i) soil organic matter content (Walkley and Black method), (ii) total soil nitrogen (Kjeldahl method), (iii) available soil phosphor (Olsen method), (iv) soil bulk density (using ring method), (v) soil hydraulic conductivity (constant head permeameter), and (vi) soil field capacity water content (see section 2.1).

3. RESULTS AND DISCUSSION

3.1 Initial soil and organic matter analysis

The results of the initial soil and organic matter analysis are presented in Table 1. The soil from Oti Village in Donggala Regency generally has low fertility. The soil texture is classified as loam, with a sand fraction of 46.4%, a silt fraction of 31.1%, and a clay fraction of 22.5%. The soil reaction (pH) was 5.95, which was slightly acidic. However, the soil organic carbon content was low at 1.17%, with available P_2O_5 also low at 9.57 ppm. Thus, utilizing this soil for agriculture would require efforts to increase its fertility, either through the addition of organic or inorganic fertilizers.

Table 1. Soil and organic matter analyses

Parameter	Value
Soil	
pH	5.95
C-organic	1.17%
P_2O_5 (Olsen)	9.57 ppm
N-total	0.18%
Organic Matter	
C-organic	17.99%
N-total	1.40%
Phosphorus	0.13%
C/N ratio	12.85

The analysis of organic matter derived from cow manure revealed a very high organic carbon content of 17.99%, with high total nitrogen (1.40%), phosphorus contents (0.13%), and a relatively ideal C/N ratio (12.85). Thus, the use of this organic matter as a soil ameliorant can help increase the availability of essential nutrients required by plants.

3.2 Early root and shoot growth

Differences in plant growth began to appear as early as six days after planting, but observations of the early root and shoot growth of the tomato plants were conducted at 20 days, as shown in Figures 1-3. The addition of organic matter to the initially infertile soil significantly improved the availability of various nutrients essential for plant growth and consistently increased early root growth across all the soil aggregate sizes studied.

No organic matter Organic matter added

Figure 1. Early root growth under <2 mm aggregate size with and without organic matter added

No organic matter Organic matter added

Figure 2. Early root growth under 2-4 mm aggregate sizes with and without organic matter added

No organic matter Organic matter added

Figure 3. Early root growth under >4-8 mm aggregate sizes with and without organic matter added

This improvement can be attributed to a suite of interconnected biological and physical mechanisms facilitated by organic matter, including enhanced soil porosity, microbial activity, nutrient availability, and hormonal interactions, which collectively create a more favorable rhizosphere environment for root proliferation. Organic matter directly influences soil structure by acting as a binding agent, promoting the formation of stable aggregates. These aggregates reduce soil bulk density (see Figure 4) by creating macro- and micropores that enhance aeration and water infiltration [14, 15]. In fine aggregates (<2 mm), coalescence between particles often leads to dense, compacted soils that restrict root penetration (Figure 1). However, the incorporation of organic matter disrupts this coalescence, as its fibrous components physically separate soil particles and increase interaggregate spaces. This structural modification lowers mechanical impedance, enabling roots to navigate the soil matrix with reduced energy expenditure [4, 13]. In coarser aggregates (>4–8 mm), organic matter further stabilizes macropores, preventing their collapse under wetting cycles and maintaining pathways for root elongation (Figure 3). The resultant porosity not only improves root penetration but also enhances oxygen diffusion, mitigating hypoxia—a critical factor for root respiration and metabolic activity [6, 16].

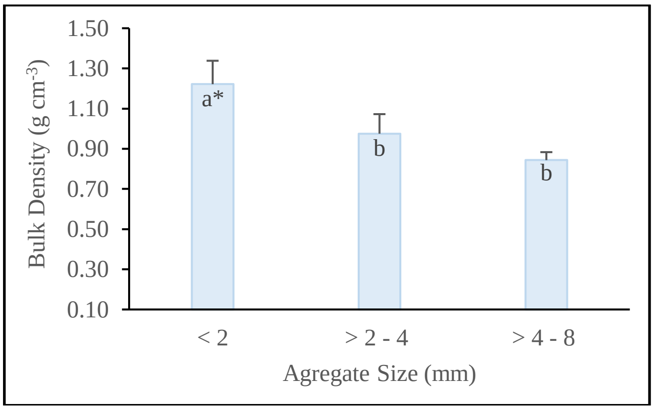

Figure 4. Effect of organic matter on soil bulk density
*Different letters in the histogram indicate significant differences at the α=5% level.

Organic matter serves as a substrate for microbial communities, stimulating their growth and enzymatic activity. Microbes decompose organic compounds, releasing labile nutrients such as ammonium, phosphate, and soluble organic acids, which are readily absorbed by roots [17, 18]. For instance, the high nitrogen content of cow manure (1.40%, Table 1) likely accelerated nitrogen mineralization, providing a steady supply of nitrogen for protein synthesis and cell division in root tips. Additionally, microbial exudates, such as polysaccharides and glomalin (produced by arbuscular mycorrhizal fungi), act as cementing agents that stabilize aggregates [1, 11]. This biologically mediated aggregation further sustains pore networks, creating a feedback loop that maintains soil structure and nutrient accessibility. Enhanced microbial activity in organic-amended soils also increases the solubilization of phosphorus—a nutrient inherently limited in the study's initial soil (9.57 ppm P_2O_5, Table 1)—through the production of phosphatases and organic acids that chelate mineral-bound phosphorus [19, 20]. Consequently, roots in organic-rich treatments exhibited denser branching and greater exploration of the soil profile (Figures 1-3), driven by localized nutrient hotspots.

The physical and biochemical changes induced by organic matter also modulate root morphology through hormonal signaling. For example, auxin—a key hormone regulating root elongation and lateral root formation—is influenced by soil microbial communities. Certain bacteria, such as Pseudomonas and Bacillus species, produce auxin precursors or degrade ethylene (a root growth inhibitor), indirectly promoting root expansion [10, 12]. Furthermore, the decomposition of organic matter releases humic substances, which have been shown to mimic auxin-like effects, stimulating root hair development and lateral root initiation [8, 21]. These hormonal interactions, combined with reduced mechanical resistance in porous soils, explain the observed synchronization between robust root systems and vigorous shoot growth (Figures 5-8).

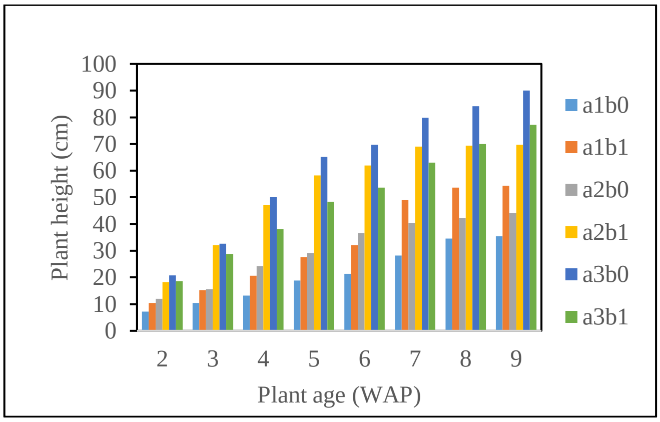

Figure 5. Increase in plant height with plant age

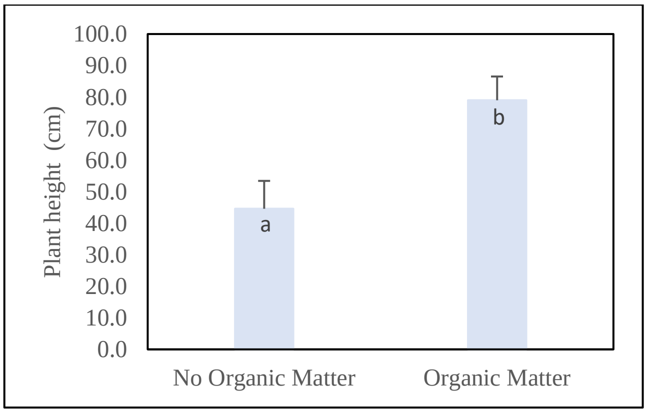

Figure 6. Effects of organic matter on plant height at 9 WAP
*Different letters in the histogram indicate significant differences at the α=5% level.

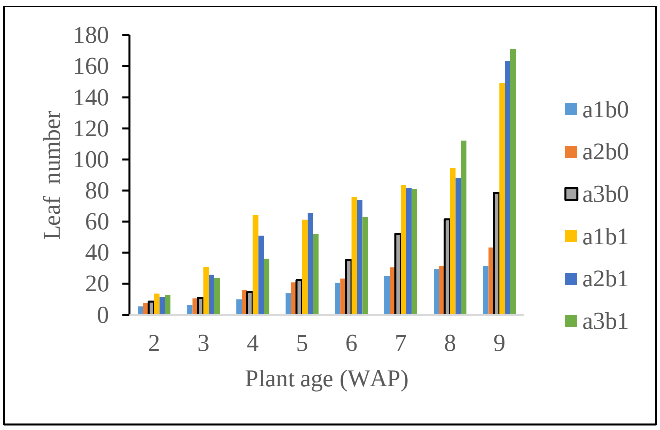

Figure 7. Increase in leaf number with plant age

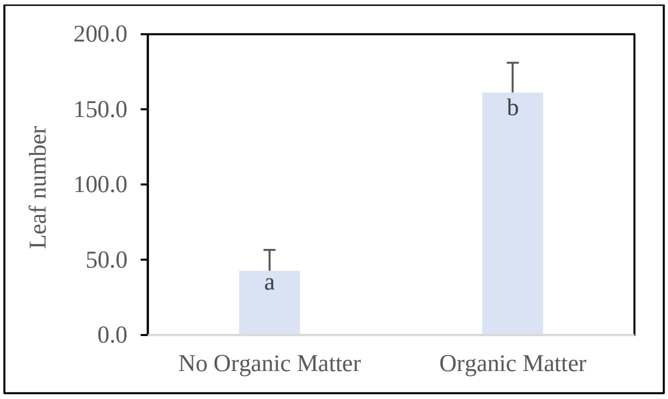

Figure 8. Effects of organic matter on tomato leaf number
*Different letters in the histogram indicate significant differences at the α=5% level.

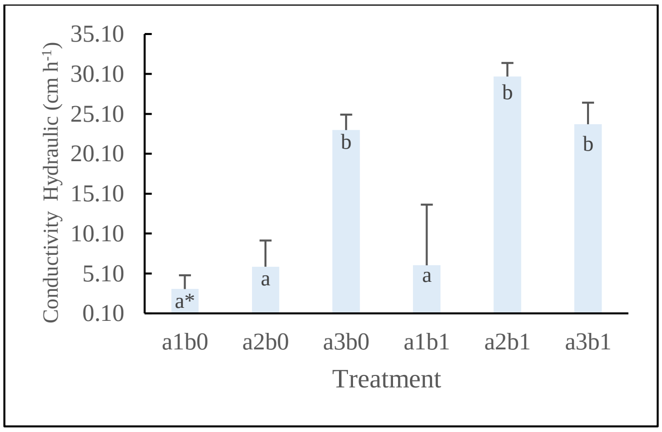

Figure 9. Effects of soil aggregate size and organic matter on hydraulic conductivity
*Different letters in the histogram indicate significant differences at the α=5% level.

Organic matter improves the soil's water-holding capacity and hydraulic conductivity (see Figure 9), ensuring consistent moisture availability during critical growth stages. In finer aggregates, organic matter mitigates waterlogging by increasing drainage through macropores, while in coarser aggregates, it enhances water retention by filling interparticle voids with organic colloids [16, 22]. This balance prevents drought stress and facilitates the passive transport of dissolved nutrients to root surfaces. Moreover, the cation exchange capacity (CEC) of organic matter retains potassium and ammonium ions, reducing leaching losses and providing a sustained nutrient reservoir [7, 22]. The resultant nutrient-rich, well-aerated, and hydrated soil environment enables roots to optimize their metabolic efficiency, allocating more resources to biomass accumulation rather than stress mitigation.

The dominance of organic matter over aggregate size in driving root growth (Figures 1-3) underscores its multifaceted role. While aggregate size influences soil physical properties (e.g., bulk density, hydraulic conductivity), organic matter exerts both direct and indirect effects: (1) physically, by restructuring pore networks; (2) chemically, by supplying nutrients and buffering pH; and (3) biologically, by fostering microbial symbionts and hormone-like interactions. These mechanisms collectively reduce abiotic stress, enhance nutrient acquisition, and promote root architectural plasticity, ultimately leading to the observed increases in root density, plant height, and yield (see Figures 5-8, 10).

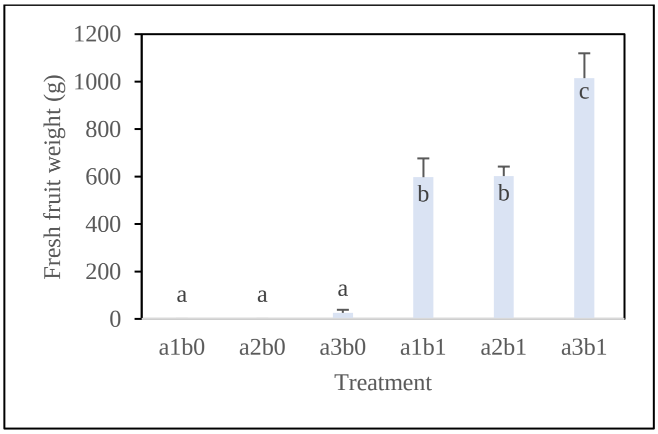

Figure 10. Fresh weight of tomatoes at harvest time
*Different letters in the histogram indicate significant differences at the α=5% level.

3.3 Vegetative growth

The height of the plants observed up to the end of the vegetative period is shown in Figure 5. Tomato plants grown in soil with added organic matter were consistently taller and significantly different from those grown in soil without added organic matter. The findings show that organic matter affects plant height between 2 and 9 weeks after planting (WAP), highlighting its significant role in contributing to the development of initial plant biomass. Although aggregate size did not significantly affect plant height, plants tended to be taller in the larger aggregate size (>4–8 mm) treatment than in the smaller (<2–4 mm) treatment, implying that large soil aggregates improve root growth in the later stages of growth. The limited impact of these two factors indicated that the combination of aggregate size and organic matter failed to produce an interactive effect at any period of observation. This finding is consistent with other studies showing that there was no affirmative interaction between aggregate size and organic content [10, 11].

This finding suggests that the >4–8 mm aggregate size tends to create more favorable conditions than the other aggregate sizes do. In fine aggregates, the soil tends to be more compact, as indicated by the soil bulk density data, leading to soil conditions that can impede root growth. Conversely, if the aggregates are too coarse (i.e., >8mm), the soil becomes very loose, reducing root-soil contact and thereby limiting the ability of roots to absorb water and nutrients. Loose soil can reduce root–soil contact, limiting water and nutrient uptake by plants [12].

Only organic matter significantly affected plant height, as shown in Figure 6, which demonstrates the final vegetative height of the plants. The plants growing in the soil with added organic matter had an average height of 79 cm, nearly twice the height of the plants growing in the soil without organic matter added (44.6 cm).

The leaf number development from 2 to 9 WAP is shown in Figure 7. Similar to plant height, leaf number was significantly affected only by organic matter, with no significant effect due to soil aggregate size. The difference in leaf count between plants grown in soil with and without organic matter added increased with plant age.

The leaf number was significantly affected only by organic matter, as shown in Figure 8. On average, plants grown in soil with organic matter had 161 leaves, four times more than the 47 leaves on plants grown in soil without organic matter. The improved nutrient availability in soil with organic matter dramatically increased leaf production.

3.4 Plant yield

The plant yield was assessed on the basis of the fresh weight of the tomato fruits. Harvesting was performed gradually by picking the fully ripe red tomatoes. Unlike plant height and leaf count, which are significantly affected only by organic matter, the individual effects of soil aggregate size, organic matter, and their interaction significantly affect the fresh weight of tomato fruits. Figure 10 shows the fresh weight of the tomatoes at harvest.

The combination treatments of <2 mm aggregate size without organic matter and >2–4 mm aggregate size without organic matter failed to produce fruit. The growth of the plants in these treatments was stunted, preventing fruit production. In the >4–8 mm aggregate size treatment, although some fruits were produced, the yield was very low. In the treatments in which organic matter was added, fruit production increased by 600 to 1000 times compared with that in the soils without organic matter. However, in the >4–8 mm aggregate size and organic matter treatment, tomato production was greater and significantly different from that in the <2 mm aggregate size and >2–4 mm aggregate size with organic matter treatments.

Overall, greater vegetative growth, as evidenced by root initiation, plant height, and number of leaves, was noted on plants grown in soils with organic matter at 10% air-dried soil mass ratio. Organic matter, which has a low C/N ratio, facilitates the release of nutrients contained within it into the soil and their absorption by plants. Importantly, there is no substitute for organic matter in terms of soil fertility and plant growth because it increases the availability of nutrients, improves the structure of the soil, and increases the level of microbial activity [13].

3.5 Soil chemical properties

3.5.1 Soil C-organic

The effects of adding organic matter (cow manure) to soil organic carbon are presented in Figure 11. These findings indicate that the level of soil C-organic matter is significantly greater in soils with added organic matter. The addition of 10% organic matter to the soil mass increased the soil organic content by up to 150%.

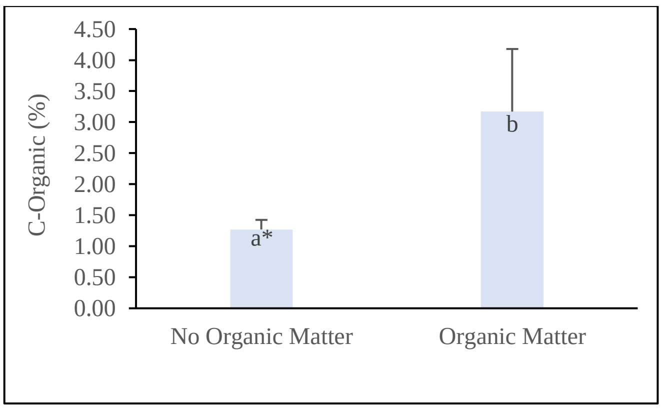

Figure 11. Effects of organic matter on the soil carbon content
*Different letters in the histogram indicate significant differences at the α=5% level.

3.5.2 Soil nitrogen-total

The total soil nitrogen data presented in Figure 12 indicate that both the individual effects of soil aggregate size and organic matter and their interaction significantly affected total soil nitrogen.

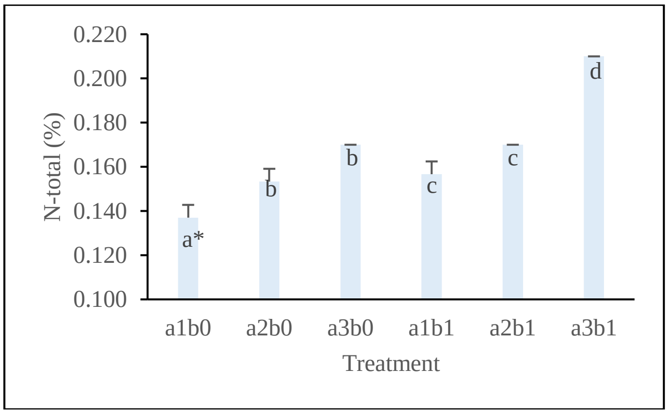

Figure 12. Effects of soil aggregate size and organic matter on total soil nitrogen

*Different letters in the histogram indicate significant differences at the α=5% level.

Figure 12 illustrates the interaction effect between soil aggregate size and organic matter application that significantly influences total soil nitrogen. Without organic matter, larger soil aggregates naturally retain more nitrogen than smaller aggregates, with the a3b0 treatment (>4–8 mm, no OM) showing the highest nitrogen retention among the soils with no organic matter added, suggesting that larger aggregates create more favorable conditions for nitrogen stabilization. The addition of organic matter significantly enhances total soil nitrogen across all aggregate sizes, with the a1b1treatment exhibiting a 50-100% increase compared to a1b0, while the mid-sized aggregates (a2b1) experience an even higher nitrogen boost, confirming the synergistic role of aggregate size and organic matter in nitrogen retention. The largest aggregates (a3b1) exhibit the most substantial increase, with nitrogen levels rising by approximately 200-300% compared to a1b0, indicating that larger aggregates with organic matter create the most optimal conditions for nitrogen retention. The overall ranking of nitrogen retention from highest to lowest is a3b1 > a2b1 > a1b1 > a3b0 > a2b0 > a1b0, showing that both larger aggregates and organic matter application positively influence nitrogen content. Enhancement occurring in large soil aggregates with organic matter, reinforcing the crucial role of both factors in soil nitrogen dynamics.

The rate of nitrogen mineralization depends on several factors, including soil microbial activity, temperature, moisture, and the carbon-to-nitrogen (C/N) ratio of organic inputs. A lower C/N ratio, such as that found in cow manure (12.85), accelerates decomposition and increases nitrogen mineralization, a microbially mediated process where organic nitrogen is converted into plant-available inorganic forms (e.g., ammonium and nitrate). Enzymatic activities, such as protease, facilitate the breakdown of proteins into amino acids, which are further mineralized by ammonifying and nitrifying bacteria [14]. Larger aggregates (>4–8 mm) enhance aeration, promoting aerobic microbial communities that accelerate organic matter decomposition and nitrogen release [19]. This explains the higher nitrogen content in soils with larger aggregates and organic matter as shown in Figure 12. Conversely, finer aggregates (<2 mm) limit oxygen diffusion, favoring anaerobic conditions that slow mineralization and increase nitrogen immobilization [10]. Thus, the interaction between aggregate size and organic matter directly modulates microbial activity and nitrogen availability.

3.5.3 Available soil phosphorus

The amount of P retained and released varies with the magnitude of the soil aggregates. As shown in Figure 13, larger aggregates tend to contain a higher concentration of organic phosphorus because of their greater organic matter content. These larger aggregates are known to contain higher concentrations of organic phosphorus because of their higher content of organic matter. On the other hand, phosphorous fractions are generally more strongly retained in smaller aggregate sizes, albeit; their general availability is comparatively lower [18, 19]. The percentage of labile phosphorus, that is easily taken up by plant roots is greater in large aggregates. Smaller aggregates, however, have better liabilities of stable phosphorus forms such as mineral-P and P associated with the organic matter, as reported by studies [18, 20].

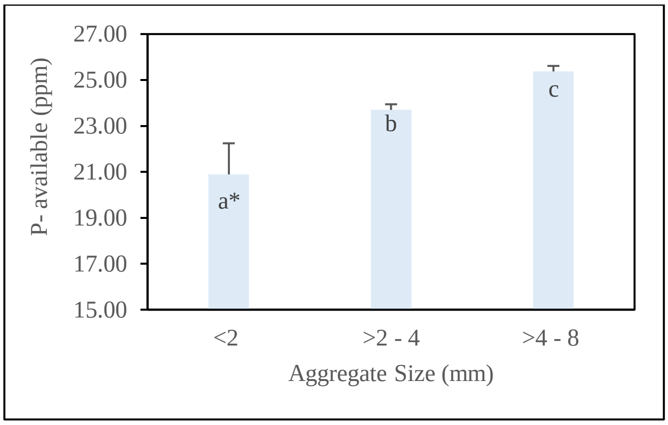

Figure 13. Effect of soil aggregate size on available phosphorus

*Different letters in the histogram indicate significant differences at the α=5% level.

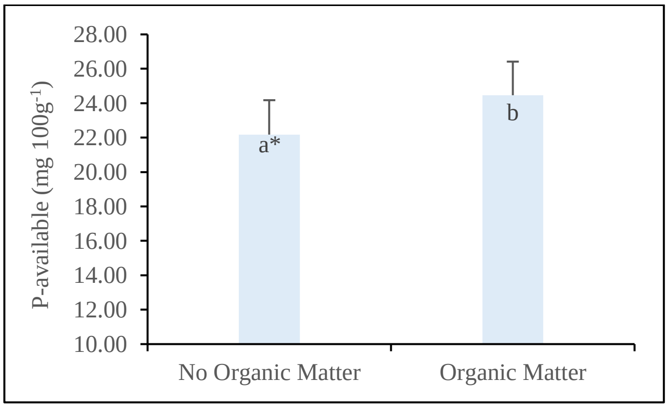

Figure 14. Effect of organic matter on available soil phosphorus

*Different letters in the histogram indicate significant differences at the α=5% level.

Continuous application of organic fertilizers such as manure enhances the effectiveness of phosphorus fertilizers in large aggregates (Figure 14). This is because these aggregates have relatively high microbial activity and relatively rich in organic matter, which leads to the stabilization and recycling of phosphorus in the soil [18, 19]. Wet sieving techniques are frequently applied in studies with the aim of sorting soil with respect to aggregate size classes. It also helps in separating the distribution of phosphorus throughout the size distribution of soil particles and how different management practices influence phosphorus behavior in the soil [19]. In contrast to the 0.5 mm aggregate size, more phosphorus desorption occurs in the aggregate size range of 4–6 mm [23].

3.6 Soil physical properties

3.6.1 Soil bulk density

With respect to the effect on soil bulk density, both the size of the soil aggregates and the organic matter separately had significant effect, but their interaction effects had not. Figure 4 compares the variation in soil bulk density in relation to the size of the aggregates, and Figure 4 displays the impact of the organic matter on the bulk density of the soil. Due to the coalescence condition of the soil, the size of the soil aggregate has a major influence; as the soil particle size becomes finer, the coalescence increases, resulting in the formation of a denser, flattened form of the soil with smaller intergranular apertures and thus lower porosity. On the other hand, coarse contents of aggregates lead to the formation of macro pore spaces that have low chances of coalescing, hence leading to the formation of loose soil. This is evident in Figure 4, which shows that the >4–8 mm aggregate size yielded the lowest mean bulk density at approximately 0.84 g cm^{-3}, which is much lower than the <2 mm and the >2–4 mm aggregate size, which had an average bulk density of approximately 1.22 g cm^{-3} and 0.98 g cm^{-3}, respectively. These changes were significant.

Adding organic matter itself caused an increase in the volume of soil, and on average, the organic matter application at 10% soil dry weight ≈ 200 t ha^{-1} significantly decreased the soil bulk density from 1.22 g cm^{-3} to 0.97 g cm^{-3}. Compared with its counterpart, the lower bulk density in the soil with added organic matter decreases the resistance of roots to penetration into the soil. High bulk density had a negative effect on root distribution (Figures 1-3). The incorporation of organic matter in the soil results in a decrease in the overall soil bulk density. Additionally, during the process of the breakdown of organic matter, some binding factors are created that aid in the formation of a stable soil structure. It also helps in the aggregation of soil particles, which in turn enhances the soil porosity and decreases the soil bulk density [14, 15, 24]. The organic matter applied to the soil at various intervals, such as during composting, and cover cropping, enhances the soil density over time. These long-term changes, affect the physical properties of the soil, reduce soil erosion, and increase the nutrient capacity of the affected soil [14, 21, 22, 25].

3.6.2 Soil hydraulic conductivity

The aggregate size and organic matter, individually and in combination, significantly affected the soil hydraulic conductivity. Figure 9 depicts the results of the interaction effect of aggregate size and organic matter on the soil hydraulic conductivity. Increased aggregate sizes increase hydraulic conductivity due to macropore formation. These larger pores cause increased water movement through the soil paths for water to take. Various research has reported that macropores provide fairly high hydraulic conductivity, especially in soil with large aggregate sizes [16, 26]. The addition of organic matter to soil has consistently been shown to increase the hydraulic conductivity of many soil types, making it easier for water to flow through the soil and improving overall soil health.

This study reveals a pronounced improvement in hydraulic conductivity when organic matter is incorporated alongside larger aggregates. This finding corroborates existing research, which has repeatedly demonstrated the efficacy of organic matter in enhancing the water-transmitting capacity by promoting water flow through the soil profile [27].

3.6.3 Water content at field capacity

The soil aggregate size can significantly affect the water content at field capacity, which is the amount of water retained by the soil after excess water has drained but before the soil becomes saturated.

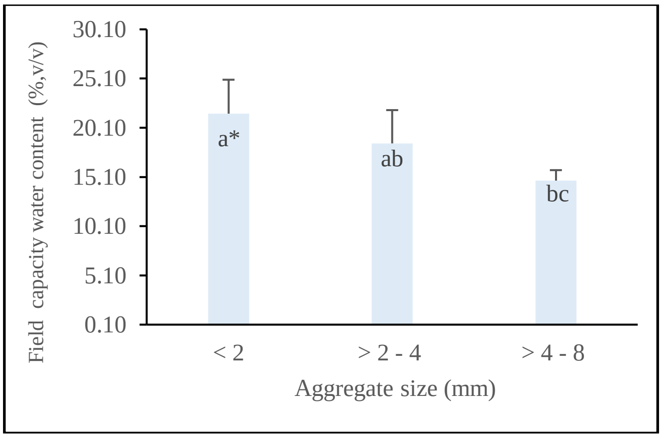

Figure 15. Effects of soil aggregate size on water content at field capacity

*Different letters in the histogram indicate significant differences at the α=5% level

Figure 15 shows larger aggregates, in particular, contain a greater proportion of macropores, which enhance drainage and reduce water retention at field capacity more than smaller aggregates do. While these macropores are vital in cases of aeration and penetration by roots, they have rather little control over the water-holding capacity. In previous studies, authors have made it clear that soil with larger aggregates possesses a lower water content at field capacity because of the enhanced rate of drainage, thus showing that aggregation affects the soil water status [16, 28, 29].

4. CONCLUSIONS

This study examines the crucial roles of soil aggregate size and organic matter (OM) in enhancing tomato growth and soil properties. The incorporation of 10% cow manure compost (OM) significantly improved early root density, plant height, and leaf count, with plants in OM-amended soils reaching an average height of 79 cm—79% taller than those in non-OM treatments (44.6 cm). Leaf production surged to 161 leaves per plant, representing a 243% increase compared to 47 leaves in non-OM soils. Most strikingly, OM application increased tomato fruit yield by a factor of 39 in the a3b1 treatment (large aggregates >4–8 mm with OM) relative to the a1b0 control (fine aggregates <2 mm without OM).

Soil physicochemical properties were profoundly influenced: larger aggregates (>4–8 mm) reduced bulk density by 31% (0.84 vs. 1.22 g cm^{-3} in fine aggregates) and increased available phosphorus by 30–40%. The interaction of OM with aggregate size amplified total soil nitrogen by 200–300% in a3b1 compared to a1b0, while hydraulic conductivity improved significantly under combined OM and large aggregate treatments. These results underscore OM's dominance in driving productivity and nutrient availability, whereas aggregate size played a primary role in optimizing soil structure and phosphorus accessibility.

Strategic integration of OM (10% by soil mass) with larger aggregates (>4–8 mm) emerges as a sustainable practice to balance soil health and crop performance. Future studies should investigate these interactions across a range of soil types and climatic conditions to refine agricultural management strategies.

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