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Interactive effects of a fermented organic extract (eco-enzyme) and balanced organic substrate on flowering of geranium (*Pelargonium hortorum*)

Sitawati[1], Masdalifa Ula[1,2*], Euis Elih Nurlaelih[1]

[1] Department of Agronomy, Faculty of Bio-Industry Agriculture and Forestry, University of Brawijaya, Veteran Street No 1, 65145, Malang City, East Java, Indonesia
[2] Master's Program in Agronomy, Department of Agronomy, Faculty of Bio-Industry Agriculture and Forestry, University of Brawijaya, Veteran Street No 1, 65145, Malang City, East Java, Indonesia
* Corresponding author's e-mail: masdalifaula@student.ub.ac.id

ABSTRACT

Container-grown geranium (*Pelargonium hortorum*) may experience delayed flowering and leaf chlorosis due to limited nutrient availability and a high carbon-to-nitrogen ratio in the growing medium. Optimizing substrate composition together with biostimulant application may therefore improve both flowering performance and ornamental quality. However, the interactive effects of eco-enzyme application and organic growing media formulation on geranium flowering remain unexplored. This study assessed the interactive effects of eco-enzyme concentration and organic growing media composition on the flowering performance of geranium. A factorial randomized block design was used, evaluating three eco-enzyme concentrations (0, 15, and 30 mL L^{-1}) and three media formulations composed of cocopeat, manure, and rice husk biochar (1:1:0, 1:1:1, and 1:1:2). The M2 medium (1:1:1) was well balanced, with favorable bulk density, porosity, and water-holding capacity that supported root development and nutrient uptake. Eco-enzyme application at 15–30 mL L^{-1} significantly ($P < 0.05$) increased flower cluster number by 31.1–59.0% in the M2 medium compared to untreated plants. The M2 medium increased flower number and cluster diameter by 18.9% and 6.3%, respectively, compared to the M3 (1:1:2) formulation, while 30 mL L^{-1} eco-enzyme increased flower number by 25.8% compared to the control. These combined effects promoted earlier, fuller flowering and greater plant vigor. Incorporating eco-enzyme biostimulant application with an optimized organic substrate therefore offers a practical and sustainable strategy to enhance geranium flowering performance and ornamental quality.

Keywords: biostimulant, flowering performance, nutrient availability, ornamental horticulture, substrate formulation.

INTRODUCTION

The increasing demand for high-quality ornamental plants has intensified the need for sustainable and efficient cultivation practices. Geranium (*Pelargonium hortorum*) is generally cultivated for ornamental purposes in containers, and its commercial value strongly depends on its compact growth, abundant flower clusters, and prolonged flowering duration. A plant with a high number of flowers, a larger cluster diameter, and bright-colored flower clusters determines market conditions and consumer preferences (Akbarzadeh et al., 2024). Geranium not only has ornamental significance but also contains bioactive nutrients, including tannins, flavonoids, and essential oils such as geraniol and linalool compounds, which generate economic and functional value (Narnoliya et al., 2019).

However, flowering performance is often poor and delayed in Indonesian pot production systems. Leaf chlorosis and decreased vigor in smaller containers with limited rooting volume are typical of these plants. These issues are mainly due to improper growing media. For low cost and high porosity, rice husk-based substrates are widely used; however, their high carbon-to-nitrogen ratio can immobilize nitrogen, leading to

nutrient deficiency and leaf yellowing (Bassan et al., 2020). As a result, fewer assimilates are spent on reproductive development in plants, resulting in fewer clusters and smaller flowers. Consequently, a good substrate must balance water retention, aeration, and nutrient supply. Cocopeat for moisture retention, manure as nitrogen, and rice husk biochar for porosity have been suggested as an alternative solution to improve root-zone environment stability (Jeon et al., 2021).

Traditional treatment of nutrient deficiencies depends on the use of synthetic fertilizers. However, organic resources and the recycling of agricultural and household residues are more widely advocated in sustainable horticulture. Eco-enzyme, a hydrolytic product obtained from the fermentation of fruit and vegetable residues, is one alternative. Hydrolytic enzymes and organic acids accelerate the decomposition of organic matter and facilitate the mineralization of nutrients (Galintin et al., 2021; Ismail et al., 2024; Vama and Cherekar, 2020). The experiment was conducted in a greenhouse located in Tegalweru Village, Dau District, Malang, East Java, Indonesia (7°56′ S, 112°34′ E, 726 m a.s.l.), from July to October 2025. The average daily temperature was 19–20°C, and the relative humidity ranged between 0.70 and 0.90. Natural daylight conditions were applied throughout the experimental period.

Despite this potential, studies investigating the interactive effects of eco-enzyme application and organic growing media formulation on plant performance remain limited, particularly in ornamental crop systems. Organic substrate formulations such as rice hulls and anaerobic digestion residues have been shown to independently influence potted geranium and rose production, without eco-enzyme application (Bassan et al., 2020)., while the enzymatic and microbial action of eco-enzyme is generally studied in relation to organic waste decomposition rather than its dependence on the substrate to which it is applied (Galintin et al., 2021; Ismail et al., 2024; Vama & Cherekar, 2020). Whether the flowering response of a container-grown ornamental species to eco-enzyme application depends on the physical and chemical properties of the growing medium therefore remains largely unexplored. This is a relevant gap, as eco-enzyme action is enzymatically and microbially mediated and may thus be constrained or enhanced by substrate aeration, porosity, and organic matter availability. We hypothesized that eco-enzyme concentration and organic growing media composition interact to influence flowering performance and ornamental quality of geranium when cultured in containers. This study therefore aimed to evaluate different cocopeat–manure–biochar ratios, identify the optimal eco-enzyme concentration, and quantify their independent and combined effects on flowering onset, flowering duration, cluster productivity, and flower color of geranium offering a substrate biostimulant strategy that is both mechanistically informed and practically applicable for ornamental crop production.

MATERIAL AND METHODS

Experimental site and growing conditions

The experiment was conducted in a greenhouse located in Tegalweru Village, Dau District, Malang, East Java, Indonesia (7°56′ S, 112°34′ E, 726 m a.s.l.), from July to October 2025. The average daily temperature was 19–20°C, and the relative humidity ranged between 0.70 and 0.90. Natural daylight conditions were applied throughout the experimental period.

Plant material and growing media

Geranium (*Pelargonium hortorum*) rooted cuttings were set up as planting materials. Plants were grown in individual plastic pots (3323.69 cm^3 volume) with organic growing media, consisting of cocopeat, goat manure, and rice husk biochar. The media was prepared in three versions in volume 1:1:0, 1:1:1, 1:1:2. All ingredients were well mixed prior to planting to maintain homogeneity.

Eco-enzyme was prepared by fermenting a mixture of molasses, mixed fruit and vegetable wastes, and water at a ratio of 1:3:10 under anaerobic conditions for at least three months. The fermentation process was initiated on September 6th, 2024, using a combination of jackfruit, banana, mango, watermelon, mustard greens (*Brassica juncea*), orange, starfruit, and papaya as organic feedstocks. Prior to its application, the eco-enzyme was characterized to determine its chemical and enzymatic properties. The solution exhibited a strongly acidic pH, ranging from 3.18 to 3.50, which is characteristic of fermented organic extracts. Enzymatic assays confirmed the presence of hydrolytic enzymes, including amylase (0.68–1.53 μmol glucose mL^{-1} min^{-1}), protease (0.41–0.75 μmol tyrosine mL^{-1} min^{-1}), and lipase (27.44–36.01 μmol fatty acid mL^{-1}

min^{-1}). Enzyme activities were determined using spectrophotometric methods, namely the Nelson–Somogyi method for amylase, the trichloroacetic acid (TCA) method for protease, and acid–base titration for lipase. The detected enzymatic activities indicate the potential of the eco-enzyme to enhance organic matter decomposition and nutrient mineralization within the growing medium.

Experimental design and treatments

The experiment was set up as a factorial randomized complete block design (RCBD) with two factors and three replications. The first factor was eco-enzyme concentration (0, 15, and 30 $mL \cdot L^{-1}$), and the second factor was the growing media composition described above. Nine treatment combinations were obtained, with each experimental unit containing 12 plants, giving a total of 324 plants. The eco-enzyme solution was applied weekly by drenching the growing media at a dose of 150 mL per plant, for a total of 12 applications throughout the experimental period.

Crop management

Basal fertilization was applied once, 14 days after transplanting, using urea (3.3 g per plant), superphosphate (SP-36; 1.13 g per plant), and potassium chloride (KCl; 2.07 g per plant), in accordance with regular advice for ornamental geranium growth. Fertilizers were added to the growing media of each pot. No further fertilization was applied during the test period so that the availability of excessive nutrients to the plants would not conceal or confound the effect of eco-enzyme treatments on plant growth and flowering response.

Measurements

Flowering characteristics

The flowering observation on a plant-by-plant basis. Flowering time was determined as the number of days between transplant and 50% of the plants in the plot blooming for the first open flower. Flower freshness duration was measured as the number of days from full flower opening (anthesis) until approximately 60% of the petals showed browning and discoloration. The total inflorescence clusters per plant were counted weekly as the number of clusters. The number of flowers was set as the number of open florets per cluster. Cluster diameter was measured at the furthest point using a digital caliper.

Flower color analysis

Flower colour was quantified using digital colorimetric software. Photographic data were taken under consistent lighting conditions. Red, green, and blue (RGB) values, along with hue, saturation, and value (HSV) parameters, were recorded.

Physical and chemical properties of growing media

Bulk density was determined as the oven-dry mass of the medium divided by its known volume ($g\ cm^{-3}$). Total porosity was calculated from the volume of water required to saturate the medium. Following free drainage, the air space was measured and defined as the air-filled porosity, while the difference between total porosity and air space was used to calculate the water-holding capacity. Media pH, organic matter content, and carbon-to-nitrogen (C/N) ratio were analyzed at three time points during the experiment 1, 40, and 80 days after transplanting following standard analytical procedures.

Statistical analysis

The experiment was arranged in a factorial randomized complete block design (RCBD). Data were analyzed using analysis of variance (ANOVA), followed by the Honestly Significant Difference (HSD) test at the 5% significance level to compare treatment means where significant main or interaction effects were detected. All analyses were performed using RStudio software.

RESULTS

Flowering time (days after transplanting)

No interaction was detected between eco-enzyme concentration and growing media composition on flowering time ($P > 0.05$). Eco-enzyme concentration alone had a significant effect on flowering time ($P < 0.05$), whereas growing media composition alone did not ($P > 0.05$). Flowering time varied more widely in M1 and M3, as reflected in wider interquartile ranges for these two media types compared to M2 (Figure 1). At the level of individual treatment combinations, the M2.E1 (15 mL L^{-1} eco-enzyme in the M2

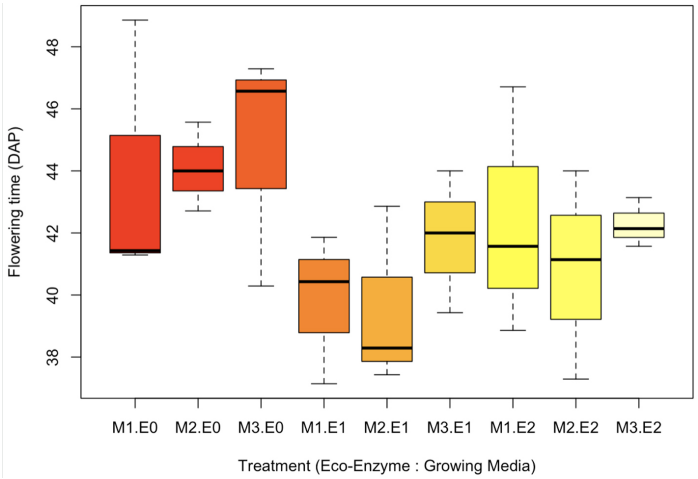

Figure 1. Effects of eco-enzyme concentration and growing media formulation on flowering time of geranium (*Pelargonium hortorum),* expressed as days after transplanting. Boxplot analysis of eco-enzyme concentration and growing media formulation on flowering time of geranium (*Pelargonium hortorum*)
Note: No interaction was observed between factors. Eco-enzyme significantly affected flowering time (Tukey's HSD 5% = 3.66), whereas growing media composition was not significant. Coefficient of variation = 7.15%

medium) combination showed both the earliest median flowering time and the narrowest interquartile range among all nine combinations, indicating a fast and uniform flowering response. In contrast, the M3.E0 (control in the M3 medium) combination exhibited the latest median flowering time together with the widest dispersion, while M1.E0 and M1.E2 also displayed comparatively wide whisker ranges, consistent with the greater variability observed in the M1 and M3 media across eco-enzyme levels. The 15 mL L^{-1} treatment (E1) produced the earliest and most uniform flowering, particularly in the balanced M2 (1:1:1) medium. Mean flowering time decreased from 44.22 days in the control to 40.38 days at 15 mL L^{-1} and 41.83 days at 30 mL L^{-1}. Only the 15 mL L^{-1} treatment flowered significantly earlier than the control (HSD 5% = 3.66); the 30 mL L^{-1} treatment was intermediate and did not differ significantly from either the control or the 15 mL L^{-1} treatment. Growing media types exhibited comparable flowering times (42.02–42.94 days; CV = 7.15%).

Flowering period (days) and number of clusters (clusters per plant)

A notable interaction between eco-enzyme concentration and the composition of the growing media was evident with respect to flowering period and the number of clusters ($P < 0.05$; Table 1). Flowering period varied from 25.08 to 29.83 days (CV = 5.31%; HSD 5% = 2.45). The application of eco-enzyme significantly extended the flowering period in M1 and M2 compared to the control, with the longest flowering period recorded in M2 at 30 mL L^{-1} (29.83 days). In M3, flowering period did not differ significantly between eco-enzyme levels (Table 1). Cluster number ranged from 1.50 to 2.56 clusters per plant (CV = 11.20%; HSD 5% = 0.36). Eco-enzyme increased cluster number in M1 and M2, with the maximum value reached at 30 mL L^{-1} in M2 (2.56 clusters), significantly exceeding all other treatment combinations. In M3, cluster number increased significantly only at 30 mL L^{-1} compared to the control. The overall eco-enzyme response was most pronounced in the balanced M2 (1:1:1) medium (Table 1).

Cluster diameter and number of flowers (flowers per cluster)

No interaction was detected between eco-enzyme concentration and growing media composition for cluster diameter or number of flowers per cluster ($P \geq 0.05$). Both factors independently affected these traits ($P < 0.05$; Table 2). At 9 weeks after transplanting, flower number increased with eco-enzyme concentration, reaching 19.81 flowers per cluster (HSD 5% = 1.77) at 30 mL L^{-1}, 17.78 at 15 mL L^{-1}, and 15.74 in the control. For media, M2 (1:1:1) produced more flowers (19.33) than M3 (16.26), while M1 (17.74) was intermediate (CV = 8.17%). The same pattern occurred in cluster diameter. Plants

Table 1. Effects of eco-enzyme concentration and growing media formulation on flowering period and number of clusters of geranium

Media formulation (cocopeat : manure : biochar)	Eco-enzyme concentration	Flowering period (days)	Number of cluster (clusters per plant)
M1 (1:1:0) / 0% biochar	0 mL L^{-1}	25.08 a	1.61 ab
M1 (1:1:0) / 0% biochar	15 mL L^{-1}	28.17 cd	2.22 cd
M1 (1:1:0) / 0% biochar	30 mL L^{-1}	28.00 cd	1.94 bc
M2 (1:1:1) / 33% biochar	0 mL L^{-1}	26.83 abc	1.61 ab
M2 (1:1:1) / 33% biochar	15 mL L^{-1}	29.33 d	2.11 c
M2 (1:1:1) / 33% biochar	30 mL L^{-1}	29.83 d	2.56 d
M3 (1:1:2) / 50% biochar	0 mL L^{-1}	27.50 abc	1.50 a
M3 (1:1:2) / 50% biochar	15 mL L^{-1}	25.17 ab	1.61 ab
M3 (1:1:2) / 50% biochar	30 mL L^{-1}	27.58 bcd	1.89 bc
HSD 5%		2.45	0.36
CV (%)		5.31	11.20

Note: Mean values followed by the same letter within the same column are not significantly different according to the 5% HSD test.

treated with 15 and 30 mL L^{-1} (10.27 and 10.93 cm, respectively) had larger clusters than the control (9.44 cm) and were comparable to each other (HSD 5% = 0.61). Medium M2 showed greater diameter (10.39 cm) than M3 (9.77 cm), but medium M1 had an intermediate diameter (CV = 5.01%) (Table 2).

Colorimetric analysis (green and blue value)

No interaction was detected between eco-enzyme concentration and growing media composition for cluster diameter or number of flowers per cluster ($P \geq 0.05$). Both factors independently affected these traits ($P < 0.05$; Table 2). At 9 weeks after transplanting, flower number increased with eco-enzyme concentration, reaching 19.81 flowers per cluster (HSD 5% = 1.77) at 30 mL L^{-1}, 17.78 at 15 mL L^{-1}, and 15.74 in the control. For media, M2 (1:1:1) produced more flowers (19.33) than M3 (16.26), while M1 (17.74) was intermediate (CV = 8.17%). The same pattern occurred in cluster diameter. Plants treated with 15 and 30 mL L^{-1} (10.27 and 10.93 cm, respectively) had larger clusters than the control (9.44 cm) and were comparable to each other (HSD 5% = 0.61). Medium M2 showed greater diameter (10.39 cm) than M3 (9.77 cm), but medium M1 had an intermediate diameter (CV = 5.01%) (Table 2).

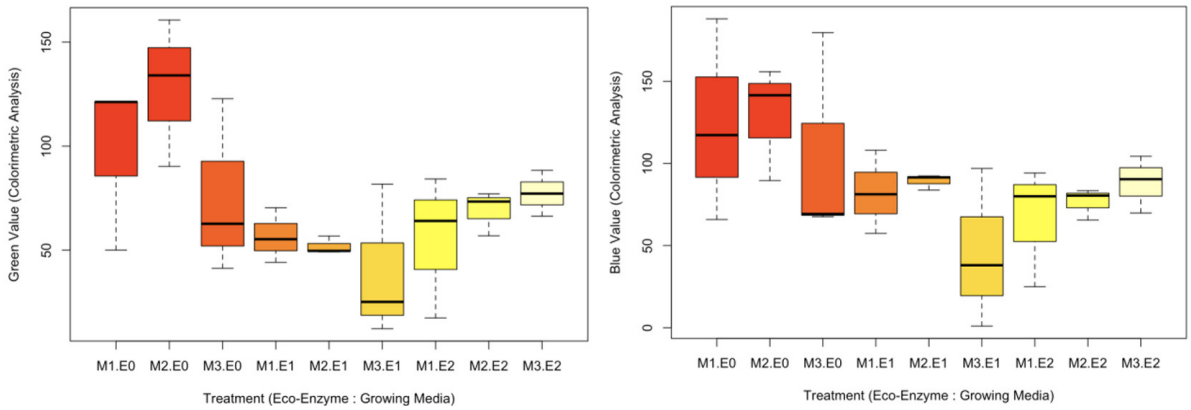

Figure 2. Effects of eco-enzyme concentration and growing media formulation on colorimetric analysis of geranium (*Pelargonium hortorum*), expressed as green (a) and blue value (b)

Note: Boxplot analysis of eco-enzyme concentration and growing media formulation on colorimetric analysis (green and blue value) of geranium (*Pelargonium hortorum*). No interaction between the eco-enzyme and growing media composition was detected. Eco-enzyme significantly affected green and blue channel values in the colorimetric analysis (HSD 5% = 28.11 and 38.50, respectively), whereas growing media composition showed no significant effect on both parameters.

Table 2. Effects of eco-enzyme concentration and growing media formulation on cluster diameter and number of flowers per cluster at 9 week after transplanting of geranium

Treatment	Cluster diameter (cm)	Number of flowers (flowers per cluster)
Eco-enzyme (mL L^{-1})		
0 mL L^{-1}	9.44 a	15.74 a
15 mL L^{-1}	10.27 b	17.78 b
30 mL L^{-1}	10.93 b	19.81 c
HSD 5%	0.61	1.77
Media formulation (Cocopeat : manure : biochar)		
M1 (1:1:0) / 0% biochar	9.88 ab	17.74 ab
M2 (1:1:1) / 33% biochar	10.39 b	19.33 b
M3 (1:1:2) / 50% biochar	9.77 a	16.26 a
HSD 5%	0.61	1.77
CV (%)	5.01	8.17

Note: Mean values followed by the same letter within the same column are not significantly different according to the 5% HSD test.

Growing media physical and chemical properties

Physical properties were strongly affected by substrate type (Table 3). Owing to the increase in rice husk biochar from M1 (1:1:0) to M3 (1:1:2), bulk density was reduced from 0.25 to 0.18 g cm^{-3}. Total porosity increased from 67.70% (M1) to 78.23% (M3), and air space increased from 22.57% to 40.62%. Correspondingly, at higher biochar content, water-holding capacity decreased from 45.13% in M1 to 37.61% in M3 (Table 3). M2 (1:1:1) showed intermediate values across all parameters. Overall, biochar inclusion improved aeration and reduced bulk density but decreased water retention capacity (Table 3). Media pH ranged from 8.1–8.6 (weakly alkaline) at 1 DAT, decreased to 6.8–7.6 (near neutral) at 40 DAT, and stabilized at 7.1–7.3 by 80 DAT, indicating a consistent shift toward pH neutrality over the cultivation period across all treatments.

Organic matter (OM) content was significantly affected by eco-enzyme concentration, media composition, and time ($P < 0.05$). OM content at 1 DAT ranged from 21.96 to 31.89%, with M1 as the maximum and M3 as the minimum. By 40 DAT, OM content had declined to 16.74–30.91%, and it further decreased to 16.91–22.34% by 80 DAT. The highest final OM content was recorded in M2 without eco-enzyme (22.34%), while the lowest was recorded in M3 with 30 mL L^{-1} eco-enzyme (16.91%), suggesting more complete decomposition under eco-enzyme application. The C/N ratio was also significantly affected ($P < 0.05$). Starting values ranged from 14 to 16, with M3 highest. The ratio declined to 8–14 at 40 DAT and stabilized at 9–10 by the end of the experiment, with the 15 mL L^{-1} treatment combined with M2 showing the greatest reduction..

DISCUSSION

Eco-enzyme and growing media effects on generative performance

Results proved that the application of eco-enzyme continually had favorable effects on the generative properties of geranium, but different compositions of growing media appeared to have either secondary or supporting effects. The earlier flowering observed at 15 mL L^{-1} eco-enzyme (Figure 1) indicates a faster transition from vegetative to reproductive development, likely due to better assimilate utilisation and availability of nutrients for floral initiation. For ornamental crops, such accelerated flowering is important for agricultural reasons, because it increases the production efficiency and market value of *Pelargonium hortorum*. This effect is consistent with biostimulant-treated plants, in which enhanced nutrient mobilization and physiological activity cause a reduction in time to flowering (Aizaz et al., 2025; Morcillo et al., 2022; Soverda et al., 2024). Mechanistically, the enzymatic constituents of eco-enzyme (protease, amylase, and lipase) presumably strengthened organic matter mineralization and, consequently, amino acids, sugars, and fatty acids as substrates for metabolism and hormonal precursors also

Table 3. Physical properties of the growing media (bulk density, total porosity, air space percentage, and water-holding capacity)

Physiscal properties of the growing media	Composition of the growing media (Cocopeat : manure : biochar)		
	M1 (1:1:0)	M2 (1:1:1)	M3 (1:1:2)
Bulk density (g cm^{-3})	0.25	0.20	0.18
Total porosity (%)	67.70	72.21	78.23
Air space (%)	22.57	30.00	40.62
Water-holding capacity (%)	45.13	42.12	37.61

became available. These substances promote gibberellin-induced flower induction by controlling major floral genes and account for the more rapid onset of flowering observed at the lower eco-enzyme dose (Aizaz et al., 2025; Kong et al., 2017).

Outside flowering time, the increase in cluster number, flower number, and cluster diameter (Table 1, Table 2) suggests that eco-enzyme enhanced sink activity in reproductive tissues and shifted the allocation of photosynthates towards floral development. This response points towards improved metabolic efficiency, rather than stimulation of vegetative growth. Similar increases in flower production after biostimulant or biofertilizer treatment have been found to be consistent with enhanced nutrient uptake, increased microbial activity in the rhizosphere, and improved hormonal balance (Carillo et al., 2022; Peron et al., 2024; Rouphael & Colla, 2020). While media composition had only a minimal effect on flowering time, the superior performance of M2 for cluster number, flower number, and cluster diameter (Table 1, Table 2) suggests that good aeration, moisture retention, and nutrient supply are essential to the success of root function and the effective application of biological inputs. The fact that the biostimulant effect is greatly influenced by root zone conditions is emphasized by this coupling of substrate structure and biochemical stimulation.

Colorimetric responses further corroborate the physiological role of eco-enzyme in regulating plant metabolism. Lower Green and Blue RGB components under eco-enzyme treatment (Figure 2) indicate increased anthocyanin accumulation and deeper flower colour. It has been reported that increased pigment synthesis after biostimulant use corresponds with stimulation of the phenylpropanoid pathway and up-regulation of both PAL and ANS enzymes involved in anthocyanin biosynthesis (Donoso et al., 2021; Gao et al., 2016; Wu et al., 2022). The weak influence of media composition on colour (Figure 2) suggests that pigment expression is primarily driven by internal metabolic processes rather than by substrate features. Taken together, these results indicate that eco-enzyme serves specifically as a biochemical catalyst in promoting nutrient turnover, hormonal signals, and metabolic activities, and that a suitable growing medium supports this process to improve flower performance and decorative quality.

Physical properties, chemical dynamics of the root zone

The principal limitation for the flowering of *Pelargonium hortorum* is slow organic matter turnover and suboptimal root-zone conditions that limit nitrogen availability and root respiration. The application of eco-enzyme systematically alleviated these restrictions, with positive effects on generative performance, flowering speed, and cluster productivity (Table 1, Table 2). These effects reflect a direct biochemical pathway rather than an elementary fertilization response. The components of eco-enzyme (protease, amylase, lipase) promote the depolymerization of organic substrates, promote heterotrophic microbial growth, and induce N, P, and K mineralization (Liu et al., 2023; Paillat et al., 2020; Yang et al., 2020). The decrease in C/N ratio observed during cultivation further supports a reduction in nitrogen immobilization and better alignment between nutrient release and plant demand, while the concurrent shift toward pH neutrality likely promoted nutrient solubility and microbial efficiency. Together, these processes help explain the earlier flowering onset at 15 mL L^{-1} eco-enzyme and the greater reproductive output observed across the eco-enzyme treatments, supporting the interpretation of eco-enzyme as a functional biostimulant that modifies rhizosphere processes rather than simply supplying nutrients.

The scale of this biochemical stimulation was strongly influenced by the physical structure of the substrates (Table 3). Experimental results

reveal that the M2 medium (33% rice husk biochar) showed consistent improvement in flowering traits over the denser M1 and more porous M3 formulations (Table 1, Table 2), indicating that it is the balance of physical structure that accounts for the best performance rather than aeration capacity alone. Small reductions in bulk density enhanced oxygen diffusion, root penetration, and microbial activity, but excess biochar caused macroporosity at the cost of water and nutrient retention (Table 3). This trade-off may help explain why the extremely porous M3 did not produce the best flowering response. The superior performance under M2 illustrates that maximal nutrient uptake requires a synergistic combination of aeration, moisture, and buffering. Comparable responses have been observed in ornamental crops, where a moderate amount of biochar improves growth while excessive quantities lead to reduced productivity (Altaf et al., 2021; Conversa et al., 2015; Lamichhane et al., 2024). Substrate physical structure thus acts as a gatekeeper that determines whether increased nutrient mineralization can be translated into a physiological benefit.

The greatest enhancements in flowering were observed under simultaneous biochemical activation and structural optimization. Flowering time was most accelerated under M2 combined with 15 mL L^{-1} eco-enzyme (Figure 1), while cluster number, flower number, and cluster diameter were progressively enhanced across both the 15 and 30 mL L^{-1} eco-enzyme treatments, particularly in the M2 medium (Table 1, Table 2). This pattern indicates a causal synergy, as superior aeration facilitates root and microbial metabolism, while enzymatic catalysis promotes nutrient turnover, together ensuring a continuous assimilate supply to reproductive sinks. The stabilization of C/N ratio within optimal limits and the shift toward near-neutral pH help avoid nutrient lock-up and maintain nutrient uptake (Mann et al., 2023; Prasad et al., 2020; Sharifi et al., 2024). From an agronomic point of view, these results reject one-factor approaches and thus advocate integrated substrate engineering that combines physical suitability with biochemical stimulation. In practice, the use of about one-third biochar with carefully controlled doses of eco-enzyme offers potential for a repeatable strategy to improve flowering quality and benefit the utilization of organic waste streams, paving the way for a scalable and sustainable development of an ornamental crop production system.

CONCLUSIONS

Eco-enzyme application and growing media composition had both interactive and independent effects on the flowering performance of *Pelargonium hortorum*, indicating that reproductive fitness is mainly mediated by biochemical stimulation coupled with optimal root-zone conditions. The optimum substrate (cocopeat : manure : rice husk biochar, 1:1:1) in combination with eco-enzyme (15–30 mL L^{-1}) was most effective in promoting flowering capacity, increasing cluster number by 31.1–59.0% in the M2 medium, flower number by 18.9%, and cluster diameter by 6.3% compared with the less optimal M3 medium. The 15 mL L^{-1} eco-enzyme treatment alone significantly accelerated flowering time by 8.7% compared to the control, while eco-enzyme application across both concentrations (15–30 mL L^{-1}) independently increased cluster diameter by up to 15.8% and the number of flowers per cluster by up to 25.8%, indicating preferential assimilate allocation toward reproductive development and improved metabolic efficiency. Overall, these findings show that eco-enzyme biocatalysis, when combined with an optimally porous and balanced substrate, offers a practical and sustainable approach to enhancing flowering precocity, cluster productivity, and ornamental quality in geranium production.

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REFERENCES

1. Aizaz, M., Lubna, Hashmi, S. S., Khan, M. A., Jan, R. (2025). Unraveling the complexities of flowering in ornamental plants: the interplay of genetics, hormonal networks, and microbiome. *J. Plants.*, *14*(7), 1. https://doi.org/10.3390/plants14071131
2. Akbarzadeh, M., Van Laere, K., De Keyser, E., Van Huylenbroeck, J., Werbrouck, S. P. O. (2024).

Interspecific hardy geranium progenies: morphological characterization and genetic evaluation. *J. Hort.*, *10*(723), 1–5. https://doi.org/10.3390/horticulturae10070723

3. Altaf, K., Younis, A., Ramzan, Y., Ramzan, F. (2021). Effect of composition of agricultural wastes and biochar as a growing media on the growth of potted stock (*Matthiola incana*) and geranium (*Pelargonium* spp). *J. of Plant Nutrition.*, *44*(7), 919–930. https://doi.org/10.1080/01904167.2020.1862205
4. Bassan, A., Bona, S., Nicoletto, C., Sambo, P., Zanin, G. (2020). Rice hulls and anaerobic digestion residues as substrate components for potted production of geranium and rose. *J. Agron.*, *10*(7), 1–18. https://doi.org/10.3390/agronomy10070950
5. Carillo, P., Pannico, A., Cirillo, C., Ciriello, M., Colla, G. (2022). Protein hydrolysates from animal or vegetal sources affect morpho-physiological traits, ornamental quality, mineral composition, and shelf-life of chrysanthemum in a distinctive manner. *J. Plants.*, *11*(2321), 1–17. https://doi.org/10.3390/plants11172321
6. Conversa, G., Bonasia, A., Lazzizera, C., Elia, A. (2015). Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of *Pelargonium* (*Pelargonium zonale* L.) plants. *J. Frontiers in Plant Sci.*, *6*(1), 1–11. https://doi.org/10.3389/fpls.2015.00429
7. Donoso, A., Rivas, C., Zamorano, A., Peña, Á., Handford, M. (2021). Understanding *Alstroemeria pallida* flower colour: Links between phenotype, anthocyanins and gene expression. *J. Plants.*, *10*(1), 1–14. https://doi.org/10.3390/plants10010055
8. Galintin, O., Rasit, N., Hamzah, S. (2021). Production and characterization of eco enzyme produced from fruit and vegetable wastes and its influence on the aquaculture sludge. *Biointerface Res. in Appl. Chem.*, *11*(3), 10205–10214. https://doi.org/10.33263/BRIAC113.1020510214
9. Gao, L., Yang, H., Liu, H., Yang, J., Hu, Y. (2016). Extensive transcriptome changes underlying the flower color intensity variation in Paeonia ostii. *J. Frontiers in Plant Sci., 6(1205),* 1–16. https://doi.org/10.3389/fpls.2015.01205
10. Ismail, A. Y., Nainggolan, M. F., Aminudin, S., Siahaan, R. Y., Dzulfannazhir, F. (2024). Characterization of chemical composition of eco-enzyme derived from banana, orange, and pineapple peels. *Brazilian J. of Biol.*, *84*(286961), 1–8. https://doi.org/10.1590/1519-6984.286961
11. Jeon, J. S., Carreno-Quintero, N., van Eekelen, H. D. L. M., De Vos, R. C. H., Raaijmakers, J. M. (2021). Impact of root-associated strains of three *Paraburkholderia* species on primary and secondary metabolism of *Brassica oleracea*. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-82238-9
12. Kong, X., Luo, X., Qu, G. P., Liu, P., Jin, J. B. (2017). *Arabidopsis* SUMO protease asp1 positively regulates flowering time partially through regulating FLC stability. *J. Integrative Plant Biology.*, *59*(1), 15–29. https://doi.org/10.1111/jipb.12509
13. Lamichhane, B., Dunn, B. L., Singh, H., Kumar, A., Norwood, F. B. (2024). Determining eastern red cedar biochar soilless-media supplementation rates for potted geranium and petunia production. *J. Hort.*, *10*(5), 1. https://doi.org/10.3390/horticulturae10050467
14. Liu, S., Liu, M., Chen, S., Ni, X., Zhang, K. (2023). Rice husks and leaf mold used as peat substitutes to improve the morphological, photosynthetic, and biochemical properties of chrysanthemum (*Chrysanthemum* × *morifolium*). *J. Sustainability (Switzerland).*, *15*(23), 1–16. https://doi.org/10.3390/su152316137
15. Mann, G. S., Dubey, R. K., Singh, S., Deepika, R., Singh, D. (2023). Effect of growing media on growth and flowering of potted marigold (*Tagetes erecta* L.) irrigated with treated sewage water. *J. Plant Nutrition.*, *46*(16), 4019–4032. https://doi.org/10.1080/01904167.2023.2220727
16. Morcillo, P. J., Gómez-Serrano, C., González-López, C. V., Massa, D., Jiménez-Becker, S. (2022). Effect of the application of hydrolysate of *Chlorella vulgaris* extracted by different techniques on the growth of *Pelargonium* × *hortorum*. *J. Plants.*, *11*(17), 1–11. https://doi.org/10.3390/plants11172308
17. Narnoliya, L. K., Jadaun, J. S., Singh, S. P. (2019). The phytochemical composition, biological effects and biotechnological approaches to the production of high-value essential oil from geranium. *J. Essential Oil Res.*, *12*, 327–352. https://doi.org/10.1007/978-3-030-16546-8_12
18. Paillat, L., Cannavo, P., Barraud, F., Huché-Thélier, L., Guénon, R. (2020). Growing medium type affects arganic fertilizer mineralization and CPND microbial enzyme activities. *J. Agron.*, *10*(12), 1. https://doi.org/10.3390/agronomy10121955
19. Peron, G., Franceschi, C., Da Dalt, C., Ferrarese, I., Sut, S. (2024). Biostimulation of *Calendula officinalis* with a soy protein hydrolysate induces flower and plant biomass and flower count by reversibly altering the floral metabolome. *J. Industrial Crops and Products.*, *214*, 1. https://doi.org/10.1016/j.indcrop.2024.118508
20. Prasad, M., Chrysargyris, A., McDaniel, N., Kavanagh, A., Gruda, N. S. (2020). Plant nutrient availability and pH of biochars and their fractions, with the possible use as a component in a growing media. *J. Agron.*, *10*(1), 1. https://doi.org/10.3390/agronomy10010010
21. Rouphael, Y., Colla, G. (2020). Editorial: Biostimulants in agriculture. *J. Frontiers in Plant Sci.*, *11*(40), 1–7. https://doi.org/10.3389/fpls.2020.00040
22. Sharifi, M., Debnath, S. C., Hajiaghaei-Kamrani, M., Rabie, B., Forsyth, J. (2024). Growing media pH and nutrient concentrations for fostering the propagation and production of lingonberry (*Vaccinium vitis-idaea* L.). *J. Agron.*, *14*(11), 1–13. https://doi.org/10.3390/agronomy14112533
23. Soverda, N., Swari, E., Neliyati, N., Putri, D., Wahyuni, D. (2024). Growth response of pak choi (*Brassica rapa* L.) on different concentrations and intervals of eco-enzyme applications. *Indonesian J. of Agron.*, *52*(1), 82–91. https://doi.org/10.24831/jai.v52i1.53868
24. Vama, L., Cherekar, M. N. (2020). Production, extraction and uses of eco-enzyme using citrus fruit waste: Wealth from waste. *J. Biotech. Env. Sci.*, *22*(2), 2020–2346.
25. Wu, Y., Hao, Z., Tang, Y., Zhao, D. (2022). Anthocyanin accumulation and differential expression of the biosynthetic genes result in a discrepancy in the red color of herbaceous peony (*Paeonia lactiflora* Pall.) Flowers. *J. Hort.*, *8*(4), 1–12. https://doi.org/10.3390/horticulturae8040349
26. Yang, Y., Awasthi, M. K., Bao, H., Bie, J., Lei, S. (2020). Exploring the microbial mechanisms of organic matter transformation during pig manure composting amended with bean dregs and biochar. *J. Bioresource Technology.*, *313*(1), 1–9. https://doi.org/10.1016/j.biortech.2020.123647