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Research Article

Optimizing frass and PGPR on the growth and yield of kailan (*Brassica oleracea*)

Undang Undang [1], Elya Hartini [1], Wafa Fauziah [1], Ristina Siti Sundari [2,*], and Farhan Ahmad [3]

[1] Agrotechnology Study Program, Faculty of Agriculture, Universitas Siliwangi, Jl. Siliwangi No. 24 Tasikmalaya, West Java 46115, INDONESIA
[2] Agribusiness Study Program, Faculty of Agriculture, Universitas Perjuangan Tasikmalaya, Jl. PETA No. 177 Tasikmalaya, West Java 46115, INDONESIA
[3] Department of Agronomy, Faculty of Crop Production Sciences, The University of Agriculture Peshawar, Peshawar, Khyber Pakhtunkhwa, PAKISTAN.
* Corresponding author (✉ ristina.sitisundari@yahoo.com)

ABSTRACT

Plant growth-promoting rhizobacteria (PGPR) and frass application have drawn interest as ways to increase plant productivity. This research aimed to evaluate the effect of frass and PGPR application on the growth and yield of kailan. The effects of varying frass dosages/F (0, 15, 20, and 25 tons ha^{-1}) and PGPR concentrations/P (0, 5, and 12.5 mL L^{-1}) on plant height, leaf number, leaf area, scaffold weight, and leaf weight per plant at 14, 21, and 28 days after planting (DAP) were examined. The growth of plants was generally enhanced by increasing dosages of frass and PGPR. The treatment F25P5 consistently produced the best results across all parameters, demonstrating its effectiveness in enhancing plant growth and yield. Positive correlations between plant height, leaf area, and leaf weight per plant (0.99) were found using correlation analysis, suggesting that leaf expansion is essential for biomass accumulation. Plant height, leaf number, and biomass-related parameters clustered together, confirming their interdependence in growth, and principal component analysis (PCA) showed that PC1 explained 94.09% of the variance. The results highlight that while excessive doses of frass and PGPR may have declining effects, balanced treatments significantly increase plant productivity. Optimizing the dosage of Frass and Rhizobia is crucial to achieving the best results for Brassica oleracea. Frass 25 tons ha^{-1} and PGPR 5 mL L^{-1} appear to be the most effective treatment.

Keywords: biofertilization; ecofriendly fertilization; *Rhizobacteria*

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INTRODUCTION

Kailan (*Brassica oleracea* var. Alboglabra) is a green leafy vegetable with high economic value. Kailan has good nutritional content for health, such as minerals, protein, vitamins, fiber, calcium, and other good content. Kailan contains vitamins A, C, E, and K, which are very high compared to other types of green vegetables (Listiani et al., 2023). The stems and leaves of kailan can be consumed fresh or processed. The stems have a sweet, crunchy, and soft taste, and the leaves taste delicious (Purniawati et al., 2017). Kailan dishes are served in various vegetable dishes on the market, especially in restaurants that serve Chinese, Japanese, European, and American cuisine. The advantages above show that kailan is one of the horticultural products with quite promising cultivation development prospects (Purniawati et al., 2017). Based on data from the Central Statistics Agency (BPS), plants from the cabbage family, including kailan plants, experienced fluctuations from 2016 to 2021 (Novatriana & Hariyono, 2020). The development of cabbage production and productivity in Indonesia from 2016 to 2021 fluctuated but tended to increase yearly, but the productivity was still low, ranging from 16 tons ha^{-1} to 22 tons ha^{-1}. This is still far behind other cabbage-producing countries, such as China at 35 tons ha^{-1} and Japan at 41 tons ha^{-1}. Therefore, Indonesia needs the proper cultivation techniques for optimal productivity in cabbage plants, especially Kailan.

Efforts to increase Kailan production can be made by fertilizing. Fertilization is one component of plant cultivation technology that meets the nutrient needs of plants to improve soil conditions so that plants can grow and develop optimally (Haryadi et al., 2015). Organic fertilizers are beneficial for increasing agricultural production in both quality and quantity, reducing environmental pollution, and sustainably improving land quality. Using organic fertilizers in the long term can increase land productivity and prevent land degradation (Simanungkalit et al., 2006). One of the materials that can be used for organic fertilizer is frass. Frass or maggot residue comes from the remaining living media of black soldier flies through the decomposition of maggots to become compost that has high utility value. Frass is one type of fertilizer that has become increasingly popular in the last decade, but the use of frass for plants is currently still lacking (Wulanningtyas & Malik, 2017). Frass can be used as an alternative organic fertilizer besides manure to improve soil fertility. The content of this frass fertilizer depends on the feed source given to frass, or maggot residue, which is the remainder of the bioconversion carried out by black soldier fly larvae, which can be used for planting media in cultivation (Novita et al., 2022). Bioreduction of waste by maggots can produce three types of products, namely maggots, which are used as animal feed rich in protein; liquid from maggot activity, which is used as liquid organic fertilizer; and solid residue of organic waste from maggot activity, which is used as solid organic fertilizer (Yuwita et al., 2022).

Maggots can decompose organic waste faster than conventional composting microbes. Maggots can decompose organic waste such as rice, vegetables, fruits, meat, and other organic waste, to help reduce environmental pollution (Kastolani, 2019). Maggots can convert and reduce waste mass by 52% to 56% (Dortmans et al., 2017). Maggots can decompose organic waste 2 to 5 times their body weight in 24 hours. One kilogram of maggots can consume 2 to 5 kilograms of organic waste daily (Listiani et al., 2023) and produce frass as a byproduct. The nutritional content of maggot by-products in the form of solid materials has a value that is no different from commercial fertilizers on the market, so the product is used as a substitute for fertilizer (Bloukounon-Goubalan et al., 2019). Frass's content depends on the food source given to the maggot or black soldier fly larvae (Sipayung, 2015).

Another method to increase Kailan plants' productivity is by adding Plant Growth Promoting Rhizobacteria (PGPR) as a biological fertilizer to optimize organic fertilizers, so it can increase the supply of soil nutrients to plants. Organic materials act as a source of energy and food for PGPR microorganisms, so that they can increase the activity of these microorganisms in providing plant nutrients (Setyawan et al., 2021). PGPR is potentially used as a biological fertilizer and developed as a biotechnology product in the agricultural sector (Hamdayanty et al., 2022).

PGPR can stimulate plant growth. Microorganisms in PGPR ensure the availability of essential nutrients for plants and increase the efficiency of nutrient use (Nandal & Hooda, 2013). PGPR is one of the biological agents of the soil microbial group that is found around plant roots, so it directly or indirectly plays a role in plant growth and development (Hafri et al., 2020). Seedling growth showed the most significant improvement with Pseudomonas, followed by Actinomycetes and $CaCO_3$ treatments. The combination of Pseudomonas + Actinomycetes (PGPR) and $CaCO_3$ further enhanced seedling development (Ningsih et al., 2021).

Research by Fauzi et al. (2022) shows that frass fertilizer significantly affects the height and wet weight of mustard greens. The optimal dose of 100 g $3kg^{-1}$ of soil gave the best results for mustard greens with a height of 38 cm and a wet weight of 220 g. In the study of Meilani et al. (2022), the provision of chicken manure frass significantly affected the growth and yield of the fantastic Alisan Variety of lettuce. The treatment dose of 6 tons ha^{-1} of chicken manure frass gave the best results for lettuce for plant height, leaf number, fresh weight of each plant, fresh weight of each plot, dry weight of plants, dry weight of roots, and root decay ratio.

Purniawati et al. (2017) reported that the provision of PGPR significantly affected the leaf number and plant height of Kailan plants. The best treatment is administering a concentration of 12.5 mL L^{-1} of water to plant height, and the best treatment is the interval of PGPR administration at 20 DAP to plant height. Administration of PGPR with a concentration of 5 mL L^{-1} to cauliflower significantly affects the time of flower crop emergence, considerable weight of the stalk, leaf area, width, fresh weight of roots, and diameter of flower crop (Anisa, 2020). This research aimed to evaluate the effect of frass and PGPR application on the growth and yield of kailan.

MATERIALS AND METHODS

This research was conducted in Pagersari, Cibeunying Village, Cimenyan District, Bandung Regency, with coordinates -6.8833, 107.6833, 800 meters above sea level (m asl) from September to November 2023. The experiment used a randomized complete block design consisting of two factors, i.e., frass and PGPR. Frass dosages/F were 0, 15, 20, and 25 tons ha$^{-1,}$ and PGPR concentrations/P were 0, 5, and 12.5 mL L$^{-1.}$

In total, 7 treatment combinations were evaluated. F0P0: Frass dose 0 ton ha^{-1} + PGPR concentration 0 mL L^{-1} (control), F15P5: Frass dose 15 tons ha^{-1} + PGPR concentration 5 mL L^{-1}, F15P12.5: Frass dose 15 tons ha^{-1} + PGPR concentration 12.5 mL L^{-1}, F20P5: Frass dose 20 tons ha^{-1} + PGPR concentration 5 mL L^{-1}, F20P12.5: Frass dose 20 tons ha^{-1} + PGPR concentration 12.5 mL L^{-1}, F25P5: Frass dose 25 tons ha^{-1} + PGPR concentration 5 mL L^{-1}, F25P12.5: Frass dose 25 tons ha^{-1} + PGPR 12.5 mL L^{-1}.

The treatment was repeated 4 times. Fisher's F test was conducted to see the effect of treatment and to find out the different treatments; further testing was carried out using Duncan's multiple range test (DMRT) at the 5% level. Moreover, a correlation analysis was performed to determine how strong the correlations between treatments are.

Experiment implementation

PGPR materials used came from boiled tofu water containing *Pseudomonas fluorescent* bacteria with a colony density of 2.45 x 10^9 CFU/ml and *Bacillus subtilis* with a colony density of 8.35 x 10^9 CFU/ml obtained from the Food Crop and Horticulture Protection Center (BPTPH) Sub Unit of PTPH Service Region V, Tasikmalaya. PGPR analysis was carried out at BPTPH Region V Tasikmalaya, and the result was shown in Table 1.

Table 1. Results of PGPR analysis.

Type of bacteria	Tested	Standard	Test result
Pseudomonas fluorescens	Colony density	≥ 10^8 CFUmL^{-1}	2,45x10^9 CFUmL^{-1}
Bacillus subtilis	Colony density	≥ 10^8CFUmL^{-1}	8,35x10^9 CFUmL^{-1}

Frass material was obtained from maggot farmers at the Tjokro Cihampelas Hotel, Bandung City. The frass fertilizer used came from organic waste from the kitchen, such as leftover vegetables, fruits, rice, etc., used as maggot feed. The compost of maggot cultivation, called frass, was used as fertilizer. The frass requirement in this study was 5.76 kg. The analysis of frass was carried out at the Soil Laboratory of the Faculty of Agriculture, Siliwangi University, as seen in Table 2.

Based on the results of the frass analysis show that the content of total N, total P, pH, and water content, nutrients has met the minimum technical requirements for solid organic fertilizer according to Permentan 2019, while the content of total K and organic C nutrients meets the minimum technical requirements for solid organic fertilizer (Fauzi et al., 2022).

Table 2. Frass analysis results.

Parameter	Result	Unit	Minimum technical requirements for soil organic fertilizer	Category
N total	2.10	%	≥ 2	Adequate
P total	2.00	%	≥ 2	Minimum
K total	1.00	%	≥ 2	Lack
C organic	7.26	%	≥ 15	Lack
C/N ratio	3.61	-	≤ 25	Adequate
pH H_2O	7.00	-	4-9	Neutral
Water Content	14.78	%	8-20	Good

Note: Minimum technical requirements for solid organic fertilizer (Ministry of Agriculture, 2011)

The next stage, seeds were sown in polybags using 4 kg planting media of soil mixed with frass according to the treatment (m/m). Inorganic fertilizers were added per polybag with the amount of 1 g KCl and 1 g TSP. Organic fertilizer and frass were applied during media preparation. The application of PGPR was carried out 3 times, namely at 7, 14, and 21 days after planting (DAP), by watering the plant root area until it reached the field capacity. Observation included plant height, leaf number, leaf area, fresh weight per plant, and leaf weight per plant (weight of above-ground biomass).

Plant height was recorded by measuring from the soil surface to the plant tip in cm. Leaf area was recorded by placing a millimeter block of paper and counting how many blocks were covered by the leaf. Fresh weight per plant was scaled for the whole plant and root weight. Data were analyzed using ANOVA. Post hoc evaluation used DMRT at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Plant height

Figure 1 shows how plant height changes at three different times: 14, 21, and 28 days after planting (DAP) in response to various combinations of frass dosages and PGPR concentrations. Plant height rose; plants grew taller when higher doses of frass and PGPR were applied, especially at later growth stages. With the highest plant height recorded under the combination of 25 tons ha^{-1} frass and PGPR 5 mL L^{-1}, the trend indicates that frass and PGPR have a good impact on plant growth. However, slight differences in plant height across treatments suggest that other physiological or environmental factors might affect the response (Hamdayanty et al., 2022).

Alattar et al. (2016) stated that using frass for plants can be beneficial because it can stimulate plant growth. The role of N, P, and K nutrients contained in frass can affect the organic nature of the soil, which affects plant growth and development. Frass also provides nutrients for PGPR bacteria so that bacteria can colonize and grow longer in plant roots because the activity of microorganisms, such as bacteria in PGPR, can survive in the rhizosphere environment.

The provision of PGPR with a lower concentration does not cause competition between bacteria in meeting their nutritional needs, so the role of bacteria in providing nutrients for plants is optimal (Hamdayanty et al., 2022). The activity of PGPR rhizobacteria in the process of fixation (binding) of free nitrogen from the atmosphere and decomposition of soil organic matter can take place properly, so that the availability of nutrients in the plant root area, especially nitrogen nutrients that stimulate plant vegetative growth, can be mobilized and absorbed properly by plants. Novatriana & Hariyono (2020) stated that PGPR should be used in wet conditions to increase the bacteria in the rhizosphere area. The wet PGPR condition serves as a supplementary intervention aimed at enriching the rhizosphere with beneficial bacterial populations. These microbes play a crucial role in enhancing nutrient uptake by facilitating the solubilization and mobilization of essential nutrients, thereby supporting plant growth and resilience.

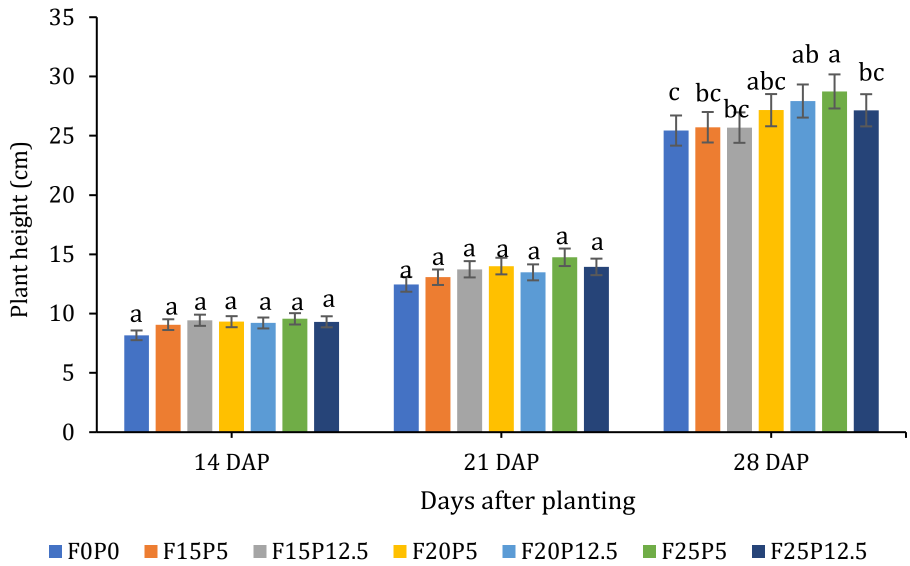

Figure 1. Kailan plant's height was affected by a combination of frass dose, PGPR concentration, and the days after planting. The same letters indicate non-significance by DMRT at α = 0.05. DAP = days after planting, F = Frass dose (tons ha^{-1}). P = PGPR concentration (mL L^{-1}).

Number of leaves

Figure 2 illustrates how various combinations of frass dosages and PGPR concentrations affect the number of leaves at 14, 21, and 28 days after planting (DAP). With the highest values reported at 28 DAP, 21 DAP, and 14 DAP, the number of leaves rose over time. Applying PGPR and frass increased the number of leaves; the highest values were found under PGPR concentrations of 5 mL L^{-1} and greater doses of frass (25 tons ha^{-1}). PGPR and frass benefit leaf development, becoming more noticeable as growth progresses. However, minor variations in the number of leaves across treatments suggest that other factors may also influence leaf growth.

The combination of frass doses and PGPR concentrations did not produce a different effect on the number of Kailan leaves at 14 and 21 DAP (Figure 2). This is thought to be due to the young plants not yet absorbing nutrients optimally, resulting in the growth of several leaves that are not yet significant.

At the age of 28 DAP, the combination of organic fertilizer doses was significantly different from the control, but not significantly different between treatment doses (Figure 2). This is thought to be because administering a combination of organic fertilizer doses with PGPR concentrations can improve the physical and chemical properties of the soil (Simanungkalit et al., 2006). The provision of frass makes the soil looser and provides nutrients for developing soil microbes. This is in line with Haryadi et al. (2015), who stated that using organic fertilizers can increase the soil's nutrient content and improve the soil's physical, chemical, and biological properties. Fertilization with organic fertilizers will improve the life of organisms in the soil because they utilize organic materials as food needed by these organisms (Nandal & Hooda, 2013). The provision of organic fertilizers will affect soil conditions so that they can provide macro elements (N, P, K) that can be helpful for plant growth and development (Pramono et al., 2023). The addition of PGPR, in addition to acting as a biostimulant, can also affect the increase in plant nutrition. The bacteria contained in PGPR produce phytohormones such as auxin, cytokinin, and gibberellin, which can stimulate cell enlargement and division so that it can increase the number of plant leaves (Achmad & Maghfoer, 2019).

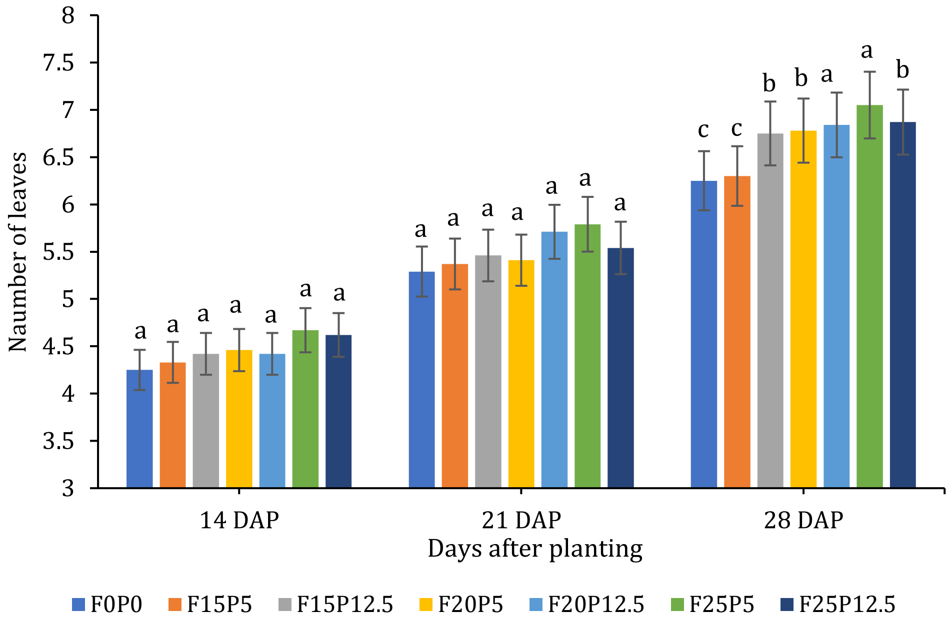

Figure 2. The number of leaves of the Kailan in different combinations of frass dose and PGPR concentration, days after planting. The same letters indicate non-significance by DMRT at α = 0.05. DAP = days after planting, F = Frass dose (tons ha^{-1}). P = PGPR concentration (mL L^{-1})

Leaf area

The impact of various combinations of PGPR concentrations and frass doses on leaf area is depicted in Figure 3. With increasing frass dose and PGPR content, the data showed a general increasing trend in leaf area, the highest was at 25 tons ha^{-1} of frass and 5 mL L^{-1} of PGPR. However, a discernible decrease in leaf area at the highest treatment suggested that applying too much PGPR and frass might have negative consequences or diminishing returns on leaf expansion. With the best findings around the Frass 25 tons ha^{-1} + PGPR 5 mL L^{-1} combination, the trend indicated that frass and PGPR benefit leaf growth. Nutrient imbalances, physiological stress, or other limiting variables may cause the drop at the highest treatment level (Pramono et al., 2023).

Leaf area was an important factor in the quality of Kailan biomass. The leaf area was the result of good photosynthesis and plant metabolism. The combination of frass dose and PGPR concentration affected the area of Kailan leaves, as seen in Figure 3.

The combination of frass doses and PGPR concentrations significantly affected the leaf area. Combining frass doses of 25 tons ha^{-1} with a PGPR concentration of 5 mL L^{-1} produced the largest leaf area because frass contains more nutrients, and the number of microorganisms was smaller. Therefore, competition between microorganisms in obtaining nutrients is lower, and the role of microorganisms in providing nutrients is maximized (Novatriana & Hariyono, 2020). The availability of more nutrients for PGPR bacteria causes bacteria to successfully colonize the roots of plants, which can be beneficial for plant growth (Hamdayanty et al., 2022). Increasing the frass dose and PGPR concentration might increase the supply of nitrogen and phosphorus to meet plants' needs. Sufficient nitrogen causes vegetative plant growth, especially leaf area, to be optimal (Pramono et al., 2023). The P element can also increase leaf area because the P element plays a role in the respiration and photosynthesis processes, so it can stimulate the growth of plant leaf area. The K element is also very important in the process of photosynthesis because the K element acts as an enzyme activator and can stimulate the growth and development of new cells in plant tissue (Wulanningtyas & Malik, 2017).

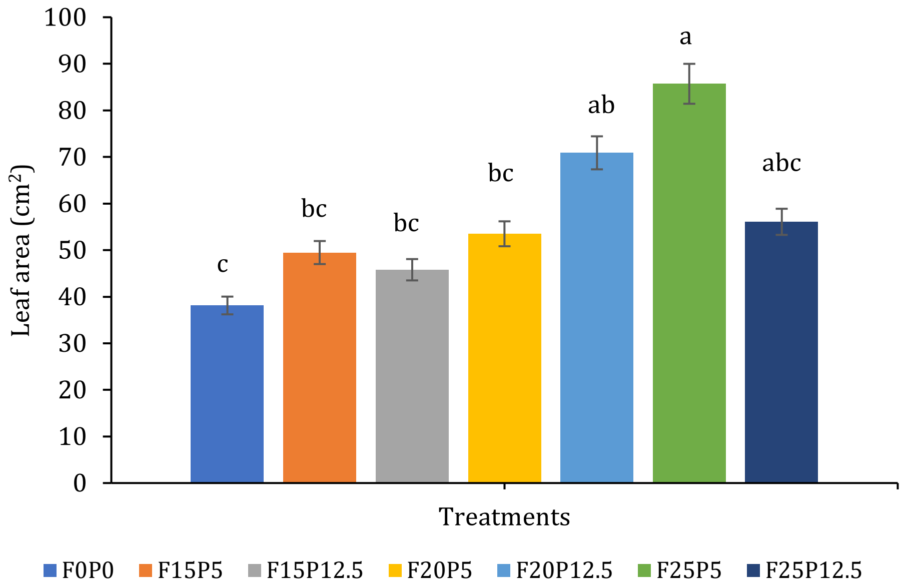

Figure 3. The Kailan plant's leaf area is affected by a combination of frass dose and PGPR concentration. The same letters indicate non-significance by DMRT at $\alpha = 0.05$. F = Frass. P = PGPR.

Fresh weight per plant

Figure 4 shows how the weight of the scaffold per plant was affected by various combinations of frass dosages and PGPR concentrations. As frass and PGPR dosages rise, the trend indicates a progressive increase in fresh weight, reaching a notable peak at the combination of frass 25 tons ha^{-1} + PGPR 5 mL L^{-1}. However, too much frass and PGPR might harm scaffold weight. Competition, physiological imbalances, or increased nutrient availability could contribute to the decline in the highest treatment level (Pramono et al., 2023).

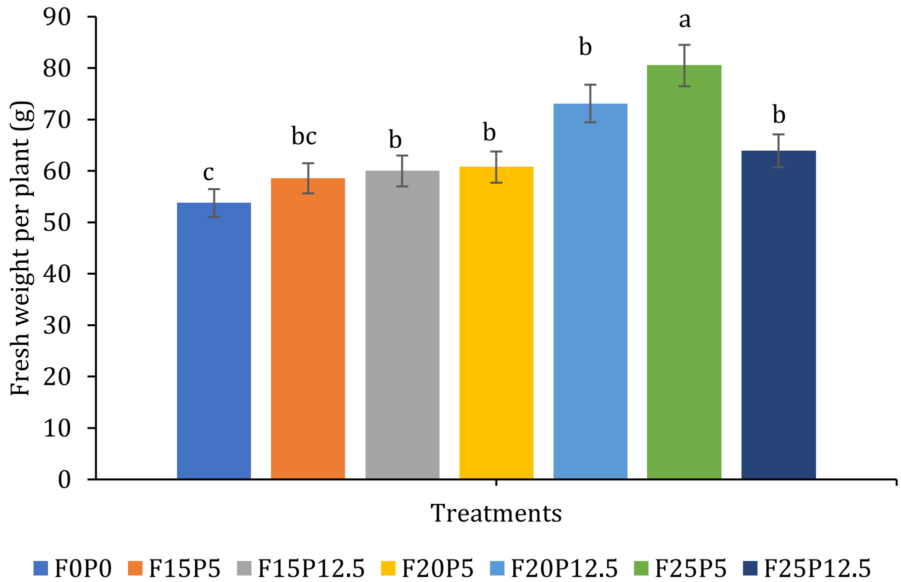

Figure 4. Fresh weight per plant (g) as affected by a combination of frass dose and PGPR concentration. The same letters indicate non-significance by DMRT at $\alpha = 0.05$. F = Frass. P = PGPR.

Combining a frass dose of 25 tons ha^{-1} and a PGPR concentration of 5 mL L^{-1} gave the highest weight of the stubble because the nutrient content of organic fertilizer is sufficient for plant growth, and competition between microorganisms is lower. The role of PGPR microorganisms in providing nutrients is maximized, so that the weight of the stubble per kale plant is significantly different (Sawal et al., 2024). Hamdayanty et al. (2022) stated that the many microorganisms in the soil can cause competition among microorganisms in obtaining food, oxygen, and water. This reduces the supply of nutrients so that microorganisms can die.

According to Rahma et al. (2014), the plant biomass increases nutrients, stimulating the development of organs in plants, such as roots, so that plants can absorb more nutrients and water. Furthermore, photosynthesis activity will increase and consequently, plant fresh and dry weight will increase.

Nutrients absorbed by plants through the roots and water will affect growth in height, number of leaves, and leaf area. The accumulation of height, leaves, and leaf area will affect the weight of the kale plant stubble (Pramono et al., 2023). The better the growth of kale plants, the higher the weight of the plant's stalks. The provision of Frass containing the nutrients N, P, and K, combined with the addition of PGPR, can increase the nutrient needs during the vegetative period of the plant, thereby increasing the weight of the stalks per plant (Nandal & Hooda, 2013). Kailan plants are harvested when they are in the vegetative phase, so they require nitrogen and phosphorus during this phase; a lack of nutrients will inhibit plant growth and development. According to Cummings (2009), PGPR can increase the absorption of $(NO_3)^{2-}$ from the soil and fixation of N_2 with its ability to absorb nutrients, supplying the N needed by plants. Rahni (2012) stated that PGPR can produce phytohormones, namely IAA, cytokinins, gibberellins, ethylene, and abscisic acid, where IAA is an active form of the auxin hormone found in plants and plays a role in increasing the quality and yield of the harvest. The function of the IAA hormone for plants includes increasing cell development, stimulating the formation of new roots, spurring growth, stimulating flowering, and increasing enzyme activity (Sawal et al., 2024).

Leaf weight per plant

Figure 5 displays the leaf weight per plant under various combinations of PGPR concentration and frass dose, showing a general upward trend as both inputs increase. Frass 25 tons ha^{-1} + PGPR 5 mL L^{-1} yielded the maximum leaf weight, indicating that this combination maximized plant development. However, leaf weight decreased at F25P12.5, suggesting that too much frass and PGPR might decline plant growth due to nutritional imbalances or overfertilization. The significance of balanced input application for maximum plant output is emphasized by this pattern, which is consistent with the scaffold weight trend.

The combination of 20 tons ha^{-1} frass + 12.5 mL L^{-1} PGPR and 25 tons ha^{-1} frass + 5 mL L^{-1} resulted in a significantly higher leaf weight than the other treatments. It can be explained by the combination of treatments, which is sufficient to supply nutrients from frass and PGPR concentration. Too high a concentration of PGPR can result in competition between microorganisms (Sawal et al., 2024; Hamdayanty et al., 2022), as shown by the leaf weight decreases with PGPR 12.5 mL L^{-1}. The leaf weight of the plant is a result of photosynthesis. If photosynthesis goes well, the photosynthate produced will also increase, so that later it will be used for the formation of organs and tissues in plants such as leaves and stems, so the higher the photosynthesis, the heavier the plant (Simanungkalit et al., 2006). Nutrients are components of organic matter that will be converted into organic components that form all plant parts. The accumulation of photosynthesis results and the absorption of nutrients results in organic compounds will form plant biomass (Dortmans et al., 2017).

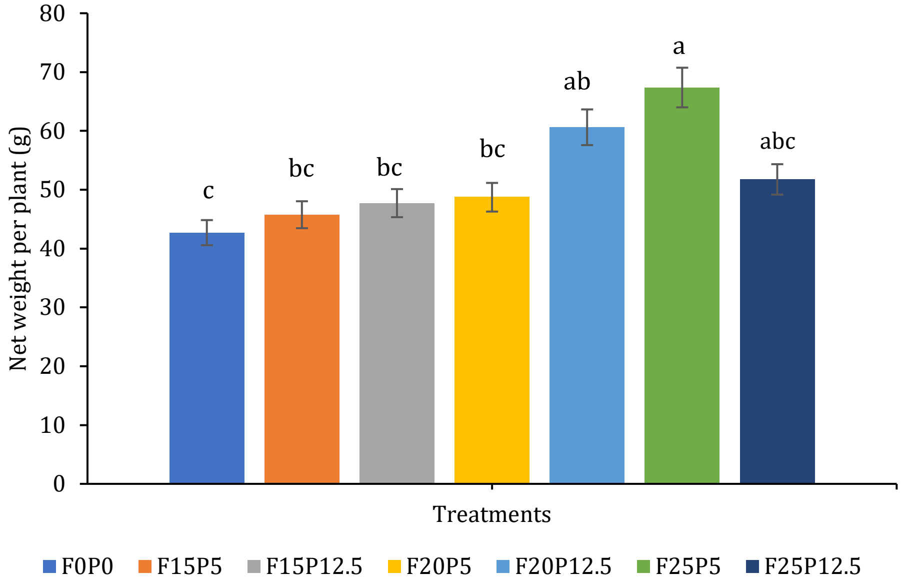

Figure 5. Leaf weight per plant is affected by a combination of frass dose and PGPR concentration. The same letters indicate non-significance by DMRT at α = 0.05. F = Frass. P = PGPR.

The provision of frass and PGPR might increase the availability of macronutrients such as N, P, and K, which would affect the growth and development of kale plants, so that their presence can affect the net weight of the plant. Providing organic materials such as frass can increase the availability of water and nutrients in the soil. This is in line with Kamilah et al. (2018), who stated that organic materials can increase the soil water holding capacity and increase aggregation ability. The application of PGPR containing *Pseudomonas* sp and *Bacillus sp* bacteria with the ability to dissolve phosphate increases P supply to the plant. Setyawan et al. (2021) stated that rhizobacteria from the *Pseudomonas* and *Bacillus sp* groups are included in significant phosphate-dissolving bacteria.

Correlation coefficients

Figure 6 represents a correlation matrix showing correlations between plant growth metrics. The color gradient indicated the correlation coefficient, with red suggesting a high positive correlation and blue indicating a negative correlation.

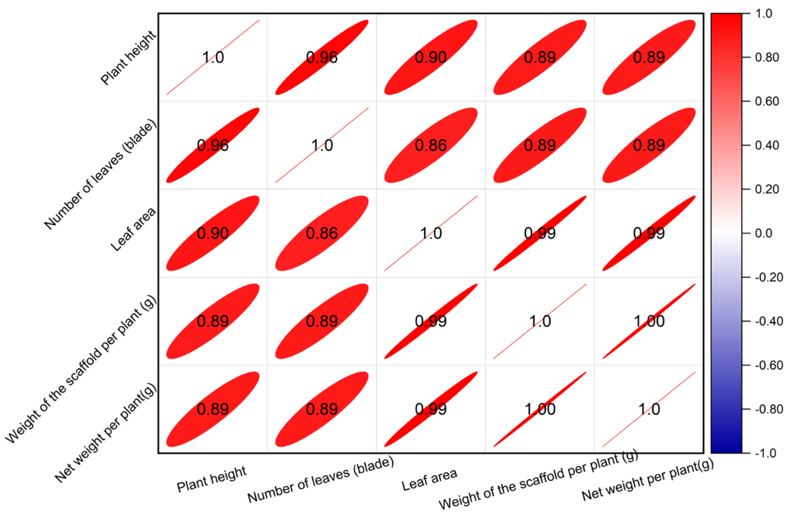

Figure 6. Correlation coefficients between plant traits.

All correlations were positive, indicating that as one parameter increases, so do the others. Plant height strongly correlated with the number of leaves (0.96) and leaf area (0.90), showing that taller plants had more and bigger leaves. The highest correlation between leaf area and leaf weight per plant (0.99) indicates that leaf expansion is critical in plant biomass accumulation. The scaffold weight per plant strongly correlated with the net weight per plant (1.0), suggesting that scaffold weight is an essential contributor to total plant mass.

Principal components

Figure 7 is a principal component analysis (PCA) biplot, which demonstrates the correlations between plant growth characteristics based on their principal components (PCs). PC1 explained 94.09% of the overall variance, while PC2 accounted for 4.86%, showing that most of the volatility in the data was captured by PC1. The vectors depicted the contributions of several plant features to the principal components, with longer vectors suggesting a more significant influence. The number of leaves and plant height had a positive correlation and are located in the upper right quadrant, indicating a close relationship in determining plant structure. Similarly, leaf area, leaf weight per plant, and scaffold weight were combined to show their contributions to biomass buildup. According to the data point placement, individual plants varied primarily along PC1, with less variance along PC2. The traits' grouping along PC1 suggests a significant correlation between biomass-related variables, plant height, and leaf count. In this instance, all qualities correlate favorably, whereas features pointing in opposing directions along PC axes suggest negative correlations.

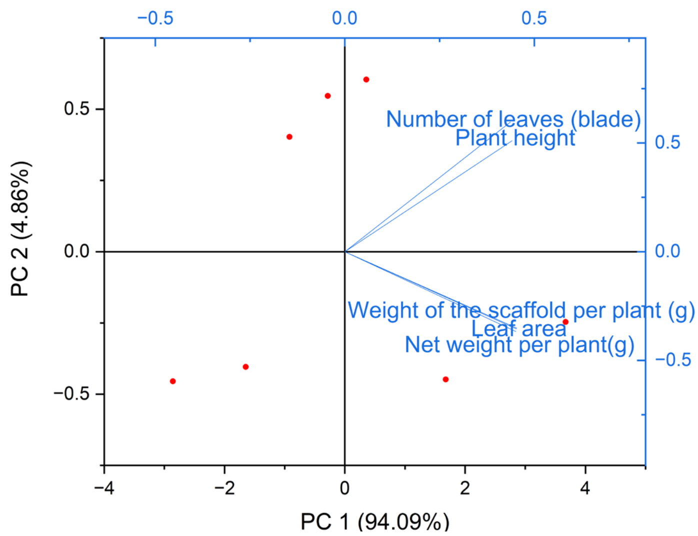

Figure 7. Principal components of the observation.

CONCLUSIONS

The treatment combination of frass 25 tons ha^{-1} + PGPR 5 mL L^{-1} consistently enhanced plant growth and yield, while excessive application (F25P12.5) led to decreased growth, likely due to nutritional imbalances or microbial competition. Strong correlations (0.99) between leaf area and leaf weight highlight the role of leaf expansion in biomass accumulation. PCA analysis shows that most growth factors cluster along PC1 (94% variation), emphasizing the interdependence of biomass-related traits. Optimizing balanced dosages of PGPR and frass is essential to prevent adverse effects, with F25P5 emerging as the most effective treatment. Future research should explore microbial interactions and long-term soil health impacts.

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