International Journal of Environment, Agriculture and Biotechnology
Vol-10, Issue-1; Jan-Feb, 2025
Peer-Reviewed International Journal
Journal Home Page Available: https://ijeab.com/
Journal DOI: 10.22161/ijeab

Optimization of Growth and Yield of Melon (*Cucumis melo* L.) on Rooftop through the Application of PGPR and Mycorrhizae

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Received: 03 Jan 2025; Received in revised form: 05 Feb 2025; Accepted: 11 Feb 2025; Available online: 15 Feb 2025

Abstract— *Melon (Cucumis melo L.) holds significant economic value but faces declining production and export rates in Indonesia due to urbanization and limited agricultural land. Rooftop farming offers a solution, albeit with challenges such as extreme microclimatic conditions and nutrient deficiencies. This study aimed to evaluate the interaction between Plant Growth-Promoting Rhizobacteria (PGPR) and mycorrhizae in optimizing melon growth and yield under rooftop farming conditions. A split-plot design with four PGPR concentrations (0, 5, 10, 15 ml/L) and three mycorrhizal doses (0, 5, 10 g/plant) was employed. Growth and yield parameters were assessed alongside microclimatic data analysis. Significant interactions were observed between PGPR and mycorrhiza on fresh root weight, total dry weight, and fruit weight. The combination of 15 ml/L PGPR and 10 g/plant mycorrhiza produced the highest improvements, with fruit weight increasing by up to 67% compared to controls. Independent effects on root length, root dry weight, plant height, and leaf count were also observed. The synergistic effects of PGPR and mycorrhiza demonstrate the potential of microbial-based approaches for enhancing crop productivity in urban agricultural systems. These findings support the development of sustainable and adaptive solutions for urban farming challenges.*

Keywords— ***Cucumis melo, mycorrhiza, PGPR, rooftop farming, synergistic biofertilizers.***

I. INTRODUCTION

Melon (*Cucumis melo* L.) holds significant economic value in the global market [1], particularly in tropical countries such as Indonesia [2]. Indonesia's melon production index peaked at 162.26 in 2020 but declined to 139.38 in 2022. Similarly, melon export volumes decreased from 69,186 kg with an FOB value of US$ 52,214 in 2021 to 25,271 kg with an FOB value of US$ 18,047 in 2022 [2]. The increasing pressure on agricultural land due to urbanization necessitates the development of adaptive cultivation methods, such as rooftop farming, which utilizes unconventional spaces for agriculture [3]. However, rooftop environments present specific challenges, including extreme microclimatic conditions [4] and limited nutrient availability [5], potentially constraining plant growth and yield.

Microbial-based approaches, such as the use of Plant Growth-Promoting Rhizobacteria (PGPR) and mycorrhizae, have proven effective in enhancing nutrient uptake efficiency [6], [7], resilience to environmental stress [8], and crop productivity [6], [9]. PGPR promotes plant growth by producing phytohormones [10] and improving nutrient availability [10], [11], while mycorrhizae establish mutualistic symbiosis to facilitate the acquisition of essential nutrients [8]. The combination of these bioagents offers substantial potential to address agronomic challenges in rooftop environments. However, studies optimizing their application for melon cultivation on rooftop remain limited. This study aims to investigate the interaction between PGPR and mycorrhizae in rooftop cultivation systems, focusing on the growth and yield of melon. The findings are expected to provide a viable

solution for urban agriculture development, particularly in melon production within urban settings.

II. MATERIALS AND METHODS

The study was conducted from January to April 2023 on the rooftop of the Faculty of Agriculture, Universitas Brawijaya, located at an altitude of 514 meters above sea level. The materials used included melon seeds of the Action 434 variety, PGPR containing *Bacillus subtilis*, mycorrhiza (*Glomus sp.*), and a growing medium composed of soil mixed with compost and rice husk charcoal. A split-plot experimental design with three replications was employed to ensure data validity. The main plot treatments (PGPR concentrations) comprised four levels: 0 ml/L (control, without PGPR), 5 ml/L, 10 ml/L, and 15 ml/L. The sub-plot treatments consisted of three levels of mycorrhizal doses: 0 g/plant (without mycorrhiza), 5 g/plant, and 10 g/plant.

Data collection in this study employed both non-destructive and destructive methods. Non-destructive observations included the measurement of plant height and leaf count, conducted twice at 24 and 44 days after planting (DAP). Destructive observations involved the analysis of fresh root weight and total dry weight of the plant, performed five times at 14, 24, 34, 44, and 54 DAP. Additional destructive measurements, such as root length and dry root weight, were taken three times at 14, 34, and 54 DAP. Additionally, fruit weight at harvest was measured. To support these measurements, environmental factors were monitored periodically to assess the range of microecosystem variables. These parameters included solar radiation intensity, air temperature, air humidity, soil temperature, and soil moisture. Solar radiation intensity was measured daily at 11:00 AM, while air temperature, air humidity, and soil temperature and moisture were recorded at 04:00 AM and 01:00 PM to capture the daily minimum and maximum values. Soil temperature was measured at a depth of 10 cm using an ITUIN soil thermometer, while soil moisture was assessed using a soil moisture meter at the same depth. Data obtained were analyzed using Analysis of Variance (ANOVA) at a 5% significance level to identify significant interactions or effects between treatments. In cases where significant results were found, further analysis was conducted using the Honestly Significant Difference (HSD) test at a 5% significance level to determine meaningful differences between treatments.

III. RESULT AND DISCUSSION

The microclimatic data collected on the rooftop during the study revealed significant variations in air temperature, soil temperature, air humidity, soil moisture, and sunlight intensity. Air temperature ranged from a minimum of 18.4–23.6°C to a maximum of 27.4–34°C. Air humidity exhibited a minimum variation of 39–80% and a maximum range of 83–99%. Sunlight intensity fluctuated widely, with the lowest recorded value at 1,316 foot-candles (FC) and the highest reaching 25,957 FC. Soil temperature showed fluctuations, with a minimum range of 20–26°C and a maximum of 28–34°C. Soil moisture varied between 21–89% at its minimum and 40–90% at its maximum. These variations provide a comprehensive overview of the rooftop's microclimatic conditions during the study, which may have influenced plant responses to microbial treatments.

Under these microclimatic conditions, the research findings revealed significant interactions between PGPR concentrations and mycorrhizal doses on fresh root weight at 34, 44, and 54 DAP, as well as on total dry weight at 34 DAP, indicating a substantial synergistic effect during specific growth phases (Table 1 and Tables 4-5). Additionally, interactions were observed in fruit weight per harvest (Fig. 1). Meanwhile, other parameters such as root length, root dry weight, plant height, and leaf count were independently influenced by either PGPR or mycorrhiza, without any interaction. PGPR promotes growth by secreting hormones such as auxin [11], [12] and enhancing nitrogen availability [13], [14]. In contrast, mycorrhiza supports phosphorus and water uptake [8], [15]. Although these mechanisms differ, they are complementary [16], contributing to improved plant growth and development. This synergy highlights the need to optimize PGPR and mycorrhizal applications during key growth stages for improved biomass and yield.

3.1 Root

Roots are essential for water and nutrient uptake as well as structural stability. Their efficiency can be enhanced through microbial associations with PGPR and mycorrhizal fungi, which improve nutrient acquisition and stimulate root growth. Mycorrhizae form hyphal networks for better phosphorus uptake, while PGPR secrete phytohormones that promote root development. The synergistic effects of these microbes on root biomass and architecture under varying application rates require further study to optimize their use for sustainable agriculture and improved productivity [17].

Table 1. Average root fresh weight at various PGPR concentrations and mycorrhizal doses

Plant age (DAP)	PGPR concentration (ml/L water)	Mycorrhiza dosage (g plant^{-1})		
		0	5	10
34	0	0.30 a	0.44 a	0.54 a
		A	A	A
	5	0.31 a	0.44 ab	0.60 b
		A	A	AB
	10	0.37 a	0.60 ab	0.87 b
		A	AB	BC
	15	0.41 a	0.82 b	1.06 b
		A	B	C
HSD 5%			0.28	
44	0	0.66 a	0.84 a	1.01 a
		A	A	A
	5	0.73 a	1.21 a	1.80 a
		A	A	A
	10	0.93 a	2.75 ab	4.28 b
		A	A	B
	15	1.65 a	5.18 b	5.67 b
		A	B	B
HSD 5%			2.20	
54	0	0.67 a	0.91 a	1.17 a
		A	A	A
	5	0.76 a	1.39 a	2.20 a
		AB	A	A
	10	1.01 a	3.23 ab	4.56 b
		AB	A	B
	15	3.05 a	6.48 b	6.80 b
		B	B	B
HSD 5%			2.33	

Note: Numbers followed by the same lowercase letter in the same row or the same uppercase letter in the same column indicate no significant difference based on the 5% HSD test. DAP: days after planting.

The fresh root weight of plants was significantly influenced by the interaction between PGPR and mycorrhiza. At 34 DAP, the application of 10 g mycorrhiza/plant combined with 15 ml PGPR/L increased fresh root weight by 158.54%. In contrast, applying 5 ml PGPR/L showed no significant difference compared to the control without mycorrhiza. These results indicate that the effectiveness of PGPR improves with higher mycorrhizal doses, accelerating root development. At 44 DAP, the combination of 10 g mycorrhiza/plant and 10 ml PGPR/L resulted in a larger increase in fresh root weight, reaching 330.22%. A further increase was observed with 15 ml PGPR/L, which enhanced fresh root weight by up to 516.67%. At 54 DAP, 15 ml PGPR/L yielded the highest fresh root weight (612.09%) at 5 g mycorrhiza/plant. The increase in fresh root weight demonstrates that higher

PGPR concentrations can support mycorrhizal symbiosis, thereby promoting optimal root development. The combination of higher doses of mycorrhiza and PGPR has been proven to support overall plant growth. These findings are consistent with previous studies by El-Sawah et al. (2021) and Chen et al. (2023).

In addition to enhancing mycorrhizal efficiency, PGPR also strengthens plant resilience against environmental stress, as reported by Galindo et al. (2024). Their research showed that PGPR increases root and plant biomass through improved CO^2 assimilation, thereby supporting photosynthetic activity, water use efficiency, and transpiration regulation. Furthermore, PGPR helps plants mitigate environmental stress by reducing oxidative stress, as evidenced by decreased reactive oxygen species (ROS) levels and membrane lipid damage. This reduction in oxidative damage is crucial for maintaining cellular integrity under stressful conditions. PGPR also promotes the synthesis of stress-related proteins that protect plant cells from environmental damage. The enhanced root growth further supports nutrient uptake, ensuring that plants maintain optimal growth even under unfavorable conditions. Consequently, PGPR applications offer a promising strategy for improving plant health and productivity in diverse agricultural systems.

Table 2. Average root length and root dry weight at various PGPR concentrations and mycorrhizal doses

Treatment	Root length (cm) ages (DAP)			Root dry weight (g) ages (DAP)		
	14	34	54	14	34	54
PGPR concentration (ml/L water)						
0	7.90	20.03	25.9 a	0.10	0.34	0.80 a
5	8.08	24.03	30.94 ab	0.10	0.37	1.15 a
10	8.27	25.78	35.9 b	0.10	0.47	2.30 ab
15	8.37	28.26	39.64 b	0.10	0.49	3.79 b
HSD 5%	ns	ns	12.42	ns	Ns	1.69
Mycorrhiza dosage (g plant^{-1})						
0	7.64	19.05 a	26.01 a	0.10	0.27 a	1.21 a
5	8.16	25.18 b	33.31 b	0.10	0.43 b	2.32 b
10	8.66	29.35 c	39.97 c	0.10	0.56 b	2.50 b
HSD 5%	ns	3.89	5.57	ns	0.13	0.99

Note: Numbers followed by the same letter within the same observation age and treatment indicate no significant difference based on the 5% HSD test. DAP: days after planting, ns: not significant.

Root length and dry weight at 54 DAP (Table 2) demonstrated a positive response to the application of PGPR and mycorrhiza. Root length increased by 53.05% with 15 ml PGPR/L, while a concentration of 10 ml PGPR/L resulted in a 38.61% increase compared to the control. Mycorrhiza also had a significant effect, with a dose of 10 g/plant increasing root length by 53.84%, and 5 g/plant leading to a 29.83% increase. Regarding root dry weight, the highest value (3.79 g) was observed at 15 ml PGPR/L, which was substantially greater than the values recorded at 5 ml PGPR/L (1.15 g) and without PGPR (0.80 g). However, reducing the concentration from 15 ml/L to 5 ml/L resulted in a marked decrease in root dry weight, with reductions of 2.99 g (78.89%) and 2.64 g (69.66%) compared to the 10 ml PGPR/L treatment (2.30 g). Mycorrhiza also showed a consistent pattern of improvement, where 5 g and 10 g/plant significantly increased root dry weight compared to the control. The observed improvements in root length and dry weight suggest that PGPR and mycorrhiza play a crucial role in supporting root development. According to Chen et al. (2023), both PGPR and mycorrhiza enhance nutrient uptake and expand root networks, which are essential for promoting plant growth. Mycorrhiza contributes to root development by improving the absorption of phosphorus, water, and other nutrients, while PGPR enhances soil microflora to support root growth [6], [11].

3.2 Shoot

Vegetative growth, marked by rapid shoot and leaf development, is significantly influenced by nutrient uptake and hormonal regulation. PGPR enhances this phase by

fixing nitrogen and secreting growth-promoting hormones such as auxins and gibberellins [11], [12], while mycorrhizal fungi improve phosphorus and water uptake through extensive hyphal networks [8], [16]. Although PGPR and mycorrhiza independently promote shoot elongation and leaf proliferation, their effects on these parameters are not synergistic. Instead, their individual contributions create favorable conditions for vegetative growth, supporting biomass accumulation during critical stages.

Table 3. The average plant length and number of leaves at various PGPR concentrations and mycorrhiza doses

Treatment	Plant length (cm) ages (DAP)		Number of leaves (unit) Ages (DAP)	
	24	44	24	44
PGPR concentration (ml/L water)				
0	35.38 a	83.27 a	7.11 a	15.81 a
5	49.61 ab	122.40 ab	9.04 ab	22.19 ab
10	66.96 bc	163.80 b	10.07 b	23.85 ab
15	79.11 c	180.90 b	10.52 b	27.70 b
HSD 5%	21.19	80.53	2.82	11.05
Mycorrhiza dosage (g plant^{-1})				
0	54.29	102.30 a	8.44 a	19.06 a
5	59.25	155.00 b	9.25 ab	23.44 ab
10	59.76	155.50 b	9.86 b	24.67 b
HSD 5%	ns	33.98	1.32	4.53

Note: Numbers followed by the same letter within the same observation age and treatment indicate no significant difference based on the 5% HSD test. DAP: days after planting, ns: not significant.

The shoot growth, comprising plant height and leaf number, significantly increased with the application of PGPR and mycorrhiza. At 24 DAP, the application of 15 ml PGPR/L increased plant height by 123.60% compared to no PGPR, though no significant difference was observed between 5 ml and 10 ml PGPR/L. At 44 DAP, treatments with 10 ml and 15 ml PGPR/L resulted in height increases of 96.71% and 117.25%, respectively, while 5 ml PGPR/L showed no significant difference from the control. Similarly, mycorrhiza at doses of 5 g and 10 g/plant improved plant height by 51.76% at 44 DAP. In terms of leaf number, the application of 10 ml and 15 ml PGPR/L increased leaf number by 41.63% and 47.96% at 24 DAP, while at 44 DAP, 15 ml PGPR/L led to a 72.04% increase compared to the control. Mycorrhiza at 10 g/plant increased leaf number by 16.82% at 24 DAP and 29.47% at 44 DAP, whereas the 5 g dose did not show a significant effect. These findings underscore the role of PGPR in enhancing nutrient availability and root activity [19] and the contribution of mycorrhiza to improved water and nutrient uptake [8], [16]. Moreover, the increase in leaf number can be attributed to the ability of PGPR to stimulate root and leaf growth [20], [21], coupled with the role of mycorrhiza in nutrient uptake efficiency, particularly during the vegetative phase [22]–[24].

3.3 Total plant biomass

Total plant dry weight is a key indicator for evaluating growth and biomass accumulation in plants, influenced by treatments such as PGPR and mycorrhiza application. Increasing PGPR concentration to 15 ml/L significantly enhanced total dry weight by 2.65 g (63.86%) compared to no PGPR (Table 4). A similar trend was observed at 44 and 54 DAP, where 15 ml/L PGPR increased dry weight by 17.12 g (77.54%) and 12.57 g (47.2%), respectively (Table 5). The highest dry weight was achieved at 15 ml PGPR/L, indicating the effectiveness of this concentration for biomass accumulation. Similarly, mycorrhiza at 10 g/plant resulted in substantial dry weight increases, with a 72.94% rise at 24 DAP and an average of 87.24% at 44 and 54 DAP compared to no mycorrhiza. Treatments without mycorrhiza consistently showed lower dry weights at all observation points.

Table 4. Interaction of PGPR concentration and Mycorrhiza dosage on average of total plant dry weight at 34 DAP

PGPR concentration (ml/L water)	Total plant dry weight (g) at 34 DAP		
	Mycorrhiza dosage (g plant^{-1})		
	0	5	10
0	10.10 a	10.47 a	9.19 a
	A	A	A
5	9.84 a	8.58 a	10.27 a
	A	A	A
10	10.84 a	11.12 a	15.74 a
	A	A	AB
15	12.57 a	28.35 b	29.25 b
	A	B	B
HSD 5%	14.13		

Note: Numbers followed by the same lowercase letter in the same row or the same uppercase letter in the same column indicate no significant difference based on the 5% HSD test. DAP: days after planting.

Table 5. The average total plant dry weight at various PGPR concentrations and mycorrhiza doses

Treatment	Total plant dry weight (g) ages (DAP)			
	14	24	44	54
PGPR concentration (ml/L water)				
0	1.52 ab	4.15 a	17.15 a	27.01 a
5	1.30 a	4.52 ab	21.64 ab	31.62 ab
10	2.25 b	5.57 ab	43.90 bc	55.77 bc
15	2.29 b	6.80 b	48.80 c	71.60 c
HSD 5%	0.89	2.62	26.59	26.99
Mycorrhiza dosage (g plant^{-1})				
0	1.73	3.77 a	20.93 a	31.12 a
5	2.03	5.50 ab	37.45 b	51.16 b
10	1.76	6.52 b	40.23 b	57.23 b
HSD 5%	ns	1.904	16.49	15.54

Note: Numbers followed by the same letter within the same observation age and treatment indicate no significant difference based on the 5% HSD test. DAP: days after planting, ns: not significant.

The synergistic effects of PGPR and mycorrhiza are underpinned by complementary physiological mechanisms. PGPR promotes nutrient uptake and enhances metabolic efficiency through the production of growth hormones like auxins [11], [12], while the observed increase in dry weight suggests the need to optimize PGPR concentrations to avoid saturation [6]. Mycorrhiza facilitates nutrient absorption by expanding root networks via mutualistic symbiosis, particularly in phosphorus-limited environments [6], [8]. These findings align with prior research indicating that the combination of PGPR and mycorrhiza enhances root and shoot biomass, especially during the vegetative phase [6].

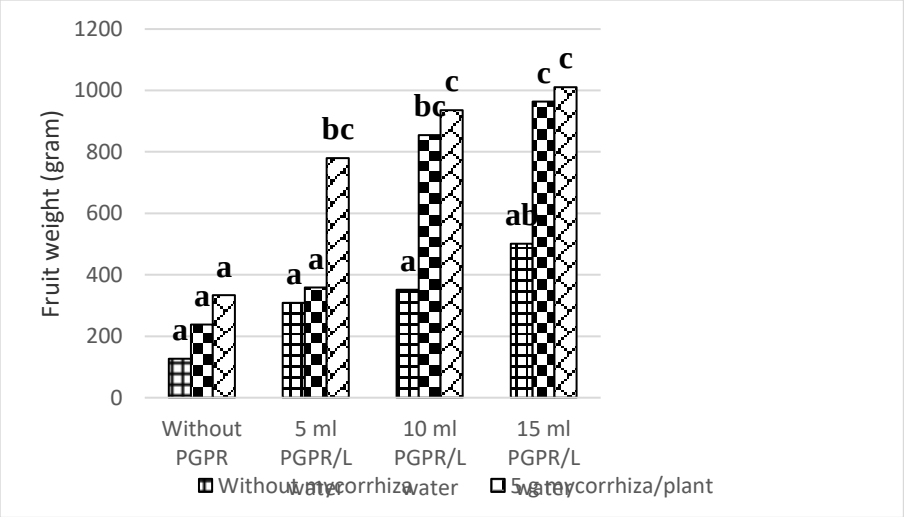

Fig. 1: Average fruit weight at various PGPR concentrations and mycorrhizal doses

Fig. 1 demonstrates that the combination of mycorrhizae and PGPR significantly influences fruit weight, which correlates with improved root and shoot growth variables. In treatments without mycorrhizae, fruit weight remained low even as PGPR concentrations increased, indicating that the effect of PGPR was not optimal in the absence of mycorrhizae. Conversely, the application of 10 g of mycorrhizae per plant produced higher fruit weights at PGPR concentrations of 5, 10, and 15 ml/L water, with respective increases of 57.18%, 64.28%, and 67.01% compared to treatments without PGPR. A significant reduction in fruit weight occurred when PGPR concentrations decreased or were not applied, underscoring the importance of synergy between these two biological agents.

These findings align with previous studies indicating that mycorrhizae enhance phosphorus uptake and the absorption of other nutrients [7], [16], while PGPR produces plant hormones such as auxins that promote growth and productivity [11], [12]. Moreover, the synergistic interaction between mycorrhizae and PGPR also impacts plant growth variables, including root elongation and shoot development, which directly affect fruit productivity. Mycorrhizae contribute by expanding the root absorption area and increasing water and phosphorus uptake efficiency, thereby supporting enhanced photosynthesis and shoot biomass [16]. PGPR complements this role by producing hormones such as auxins and gibberellins that accelerate root growth and establish a stronger and more efficient root system [12]. This combination optimizes the plant system, substantially increasing fruit weight by up to 67% compared to treatments without PGPR or mycorrhizae.

IV. CONCLUSION

This study demonstrated the synergistic interaction between PGPR concentrations and mycorrhizal doses in enhancing the growth and yield of melon in a rooftop farming system. The combination of 15 ml/L PGPR and 10 g/plant mycorrhiza significantly improved root and shoot development, especially fruit weight achieving up to a 67% increase compared to control treatments. These findings highlight the potential of integrating microbial-based approaches to address the challenges of urban farming, including nutrient limitations and extreme microclimatic conditions. Furthermore, the results provide a basis for optimizing microbial applications to enhance crop productivity in non-conventional agricultural environments. Future research should focus on evaluating the long-term effects and scalability of these practices in diverse urban contexts.

ACKNOWLEDGEMENTS

This research was supported by the Professor Grant, sourced from the Faculty of Agriculture, Universitas Brawijaya.

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