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Optimization of melon growth and nutrient assimilation using M-Bio biofertilizer foliar spray under nutrient film technique (NFT) hydroponics

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Abstract: Inthanon RZ F1 is a premium melon variety that is frequently cultivated in hydroponic systems, where optimal growth relies heavily on nutrient availability and use efficiency. Foliar biofertilizers enhance nutrient assimilation, especially in Nutrient Film Technique (NFT) systems with constrained root absorption. This study evaluated the efficacy of M-Bio, a microbial biofertilizer containing phytohormones and functional microbes, on the nutrient uptake and agronomic traits of NFT-grown Inthanon melons. A completely randomized design tested five M-Bio concentrations (0, 5, 10, 15, and 20 mL/L) across four replications. Evaluated parameters included plant height, stem diameter, leaf number, fruit weight, total soluble solids (°Brix), fruit morphology, harvest time, and macronutrient (N, P, K) uptake. Data were analyzed using ANOVA. M-Bio significantly increased stem diameter, fruit weight, °Brix, and nutrient uptake. While nutrient uptake increased by 50 to 60% at higher concentrations, the 15 mL/L treatment provided the optimal balance of improved fruit quality and accelerated harvest time. The 20 mL/L concentration further elevated nutrient absorption but yielded no additional agronomic gains. Conclusively, applying 15 mL/L of M-Bio is recommended to maximize growth, nutrient efficiency, and fruit quality in NFT-cultivated Inthanon melons.

Keywords: Nutrient Film Technique (NFT); Hydroponics; yield-contributing trait; sustainable agriculture

Introduction

Melon (*Cucumis melo* L.) is a high-value horticultural crop increasingly cultivated in soilless systems to meet consumer demand for quality fruit and to overcome the nutritional inefficiencies of soil-based production (Yang et al., 2023). Unabsorbed nutrients in traditional farming often disperse into the environment, thereby reducing economic profitability (Barłóg, 2023). In contrast, hydroponic systems, particularly the Nutrient Film Technique (NFT), optimize growth conditions by delivering water and nutrients directly to plant roots (Mendonça et al., 2023). NFT serves as a dynamic strategy that ensures a continuous nutrient supply while supporting efficient aeration for root respiration. While traditional farming is highly vulnerable to fluctuating environmental conditions, greenhouse-based NFT systems provide a controlled environment, minimize water usage, lower the risk of soil-borne diseases, and reduce agricultural dependency on arable land (Baiyin et al., 2021; Hosseini et al., 2021). Furthermore, by optimizing water and nutrient use, NFT addresses the increasingly critical need to reduce the environmental impact of agriculture (Palmitessa et al., 2024). However, the restricted root zone in NFT systems can limit nutrient uptake efficiency, making strategic interventions essential to mitigate this constraint (Husnaeni and Setiawati, 2018; Suhl et al., 2019).

Sophisticated farming systems are necessary worldwide to satisfy growing food demands. Numerous studies have demonstrated that integrating beneficial bacterial strains can significantly enhance crop production and nutritional content (Jiménez-Gómez et al., 2017). In hydroponic environments, the foliar application of biofertilizers offers distinct advantages. Because leaves act as the primary photosynthetic organs and key sites for environmental material exchange, foliar feeding can directly stimulate metabolism, enhance nutrient absorption, and increase plant tolerance to abiotic stress (Saa et al., 2015). Biofertilizers also promote root development and strengthen plant immune responses, ultimately improving yield and fruit quality under controlled conditions (Ram et al., 2024). Previous research indicates that biofertilizers, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizae, significantly improve melon growth and yield across various settings, including rooftop and hydroponic farming (Bayu et al., 2025).

Specific biofertilizers, such as M-Bio, contain functional microorganisms like *Azospirillum*, *Bacillus*, and *Pseudomonas*. These bacteria increase nutrient availability and stimulate plant growth through hormone production and nutrient solubilization, enhancing crop yields without causing environmental harm (Jiménez-Gómez et al., 2017). Foliar applications of these microbes have successfully improved vegetative growth, nutrient uptake, and fruit quality in horticultural crops. For example, strains of *Pseudomonas* sp., *Bacillus megaterium*, *Bacillus licheniformis*, and *Bacillus amyloliquefaciens* have been shown to enhance both yield and vitamin C content (Ochoa-Velasco et al., 2016), while *Bacillus* species improve growth,

yield, and antioxidant levels in strawberries (Rahman et al., 2018). Additionally, bacterial genera such as *Pseudomonas*, *Acinetobacter*, and *Bacillus* can antagonize potential phytopathogens like *Fusarium*, *Trichoderma*, and *Erwinia* species. By increasing plant nutrient elements (PNE), these microorganisms broadly improve crop quality (Yildirim et al., 2011). Furthermore, foliar biostimulants can enhance plant growth indirectly by modulating microbial communities in the phyllosphere (Luziatelli et al., 2019).

To maximize the adoption of modern agricultural innovations, commercial accessibility is crucial. M-Bio is commercially available in Indonesia, facilitating its practical application in the cultivation of melons and other crops. However, precise data on nutrient uptake requirements are necessary to develop effective nutrient management strategies and fertilizer recommendations. Establishing these data-driven recommendations is essential for optimizing melon yields. Therefore, this study aims to evaluate the effects of foliar M-Bio application on the nutrient uptake and agronomic traits of *Cucumis melo* cultivated in an NFT system, providing a foundational framework for future research and practical application.

Results and discussion

Characteristics of M-Bio biofertilizer

Quality analysis of the M-Bio biofertilizer revealed notable concentrations of three major phytohormones: auxin, cytokinin, and gibberellin (Table 1). Auxin and cytokinin were detected at 146 ppm and 66 ppm, respectively. Gibberellin was the most abundant hormone, reaching a concentration of 17,706 ppm, which is exceptionally high compared to typical microbial biofertilizers. This elevated gibberellin level suggests a strong capacity to promote cell elongation, cell division, and generative growth. Previous studies demonstrate that microbial-derived gibberellins significantly enhance shoot and fruit development by regulating key physiological pathways (Bottini et al., 2004; Nabati et al., 2025). Therefore, the hormonal profile of M-Bio provides a robust biochemical foundation for its efficacy as a plant biostimulant.

Functional microbial analysis identified a diverse consortium of beneficial microorganisms within M-Bio. *Saccharomyces* sp. and *Bacillus* sp. were present at concentrations of 2.5×10^8 CFU/mL and 5.2×10^8 CFU/mL, respectively, while *Lactobacillus* sp. was recorded at 1.3×10^6 CFU/mL. Notably, nitrogen-fixing bacteria exhibited an exceptionally high population density of 1.81×10^{11} CFU/mL, indicating substantial potential for biological nitrogen fixation even when applied via foliar pathways. Furthermore, phosphate-solubilizing bacteria were abundant (1.01×10^8 CFU/mL), facilitating the conversion of insoluble phosphate compounds into bioavailable forms for plant uptake. The synergistic presence of these microbial groups enhances nutrient mobilization and supports plant physiological processes through nitrogen fixation, phosphate solubilization, and the synthesis of growth-promoting compounds. This diverse microbial community underscores the functional value of M-Bio as an effective biofertilizer for hydroponic systems.

Pathogenicity testing yielded a negative hypersensitivity reaction, confirming that M-Bio exerts no harmful or pathogenic effects on the host plants. This lack of pathogenicity ensures that the product is safe for agricultural application and suitable for integration into sustainable cultivation frameworks. Additionally, microbial contaminant analysis demonstrated that *Escherichia coli* and *Salmonella* sp. levels were both below the detectable threshold (<3 MPN). Consequently, M-Bio complies with the safety requirements established by the SNI 7763:2018 standard, guaranteeing that the product is free from harmful microbial contamination and safe for both agricultural and environmental use.

Table 1. Quality assessment of M-Bio biofertilizer based on phytohormone content, functional microbial composition, pathogenicity, and contaminant levels.

Parameter	Unit	Result	Method
A. Phytohormones			
Auxin	ppm	146.00	Calorimetry, HPLC
Cytokinin	ppm	66.00	Chromatography, HPLC
Gibberellin	ppm	17,706.00	Chromatography, HPLC
B. Functional microorganisms			
Saccharomyces sp.	CFU/mL	2.5×10^8	Total Plate Count
Bacillus sp.	CFU/mL	5.2×10^8	Total Plate Count
Lactobacillus sp.	CFU/mL	1.3×10^6	Total Plate Count
N-Fixing Bacteria	CFU/mL	1.81×10^{11}	JNFB Media
Phosphate Solubilizing Bacteria	CFU/mL	1.01×10^8	ISK/ITSL/LBTIO2 (Quantitative-Total Plate Count)
C. Pathogenicity	-	Negative	Reaction of Hypersensitivity
D. Contaminant levels			
E. coli	MPN	< 3	SNI 7763 :2018 point 6.1l.l
Salmonella sp.	MPN	< 3	SNI 7763 : 2018 point 6.1 1.2

Note: M-Bio biofertilizer was analyzed at Soil fertility and plant nutrition laboratory of Universitas Padjadjaran.

The combined hormonal and microbial profiles of M-Bio indicate a strong capacity to enhance plant growth and nutrient use efficiency. The high gibberellin content, alongside key functional microbes such as nitrogen-fixing and phosphate-solubilizing bacteria, provides a synergistic mechanism that promotes vegetative growth, reproductive development, and overall plant health. Furthermore, the verified absence of pathogens and contaminants confirms that M-Bio is a safe and effective biofertilizer for application in hydroponic systems such as NFT.

Agronomic performance

Results showed that the application of M-Bio biofertilizer had a significant effect on stem diameter (Fig. 1). Statistical analysis of stem diameter using ANOVA followed by Duncan's Multiple Range Test (DMRT) showed significant differences among treatments (P = 0.0005). The calculated F-value (9.4314) exceeded the F-table values at both the 5% (3.056) and 1% (4.893) significance levels, confirming the significance of treatment effects on stem diameter. The relatively small standard error (SE) values observed were associated with the low coefficient of variation (CV = 4.67%), indicating high experimental precision and good data uniformity. In addition, the experiment was conducted under controlled greenhouse conditions using an NFT hydroponic system, which minimized environmental variability among replicates. Plants in the control group (P1 = 0 mL/L M-Bio) recorded a mean stem diameter of 6.81 ± 0.10 mm, which was significantly lower ($p < 0.05$) than all groups receiving M-Bio applications. Treatments P2 (5 mL/L) through P5 (20 mL/L) produced increased stem diameters of 7.85 ± 0.32 mm, 7.90 ± 0.15 mm, 8.29 ± 0.11 mm, and 7.93 ± 0.13 mm, respectively. Although statistical analysis revealed no significant differences among the four M-Bio concentrations, all treated plants exhibited significantly thicker stems compared to the control. Ultimately, the P4 treatment (15 mL/L) yielded the largest overall stem diameter at 8.29 ± 0.11 mm.

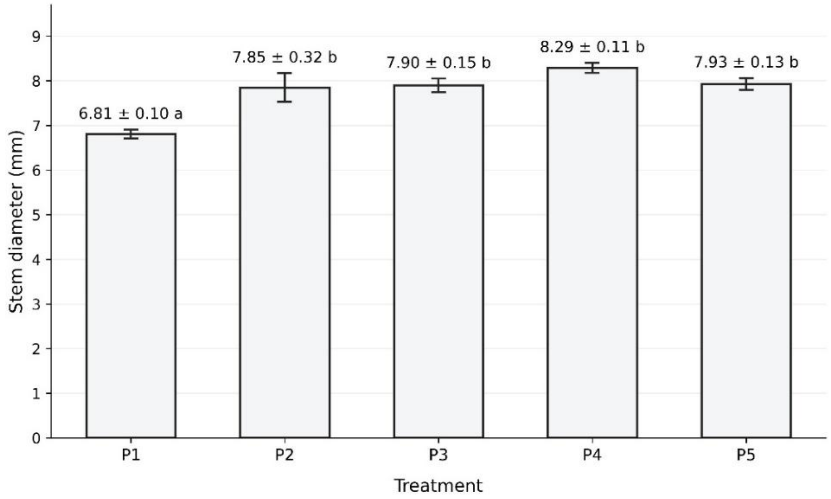


Fig. 1. Effect of M-Bio biofertilizer on stem diameter of melon grown in an NFT hydroponic system. P1 = 0 mL/L M-Bio; P2 = 5 mL/L M-Bio; P3 = 10 mL/L M-Bio; P4 = 15 mL/L M-Bio; and P5 = 20 mL/L M-Bio. Values are presented as mean ± standard error (SE). Different lowercase letters indicate significant differences among treatments according to Duncan's Multiple Range Test (DMRT) at $p < 0.05$..

The observed increase in stem diameter indicates enhanced vegetative growth, a process closely linked to the activity of vascular cambium tissues. This cambial activity is fundamentally driven by the availability of nutrients and growth hormones, particularly auxins and gibberellins, which stimulate cell division and elongation (Alori and Babalola, 2018). The functional microbes present in M-Bio, such as *Bacillus* sp. and *Saccharomyces* sp., synthesize phytohormones and enhance the uptake of nitrogen and phosphorus, directly supporting secondary stem growth. These findings align with previous research demonstrating that optimal doses of microbe-based biofertilizers improve stem growth, biomass production, and overall plant vigor, whereas excessive application rates do not necessarily yield further growth enhancements. Furthermore, gibberellins produced by rhizosphere microbes play a critical role in stimulating radial stem expansion by regulating tissue differentiation. Consequently, the significant stem thickening observed in M-Bio treated plants highlights the dual function of this biofertilizer in simultaneously facilitating nutrient assimilation and stimulating developmental hormonal activity (Bottini et al., 2004; Nabati et al., 2025).

The statistical analysis of the effect of M-Bio biofertilizer application on fruit weight is presented in Fig. 2. The ANOVA results demonstrated that M-Bio application significantly affected fruit weight, as indicated by the calculated F-value (3.859), which was higher than the F-table value at the 5% significance level (3.056), with a probability value of 0.024. Mean separation was further evaluated using Duncan's Multiple Range Test (DMRT). The coefficient of variation (CV) for fruit weight was relatively low (7.28%), indicating acceptable experimental accuracy and relatively uniform data distribution among treatments. Foliar applications of M-Bio significantly influenced the final fruit weight per plant. Plants in the control group (P1 = 0 mL/L) yielded an average fruit weight of only 1.01 ± 0.04 kg/plant. Although applying M-Bio at concentrations of 5 mL/L (P2) and 10 mL/L (P3) increased fruit weights to 1.13 ± 0.06 kg/plant and 1.14 ± 0.05 kg/plant, respectively, these values did not differ significantly from the control. The most substantial improvement occurred in the 15 mL/L treatment (P4), which produced the highest average fruit weight of 1.23 ± 0.02 kg/plant, representing a statistically significant increase over the control. At the highest concentration of 20 mL/L (P5), the fruit weight decreased slightly to 1.17 ± 0.02 kg/plant but remained elevated relative to the unfertilized plants.

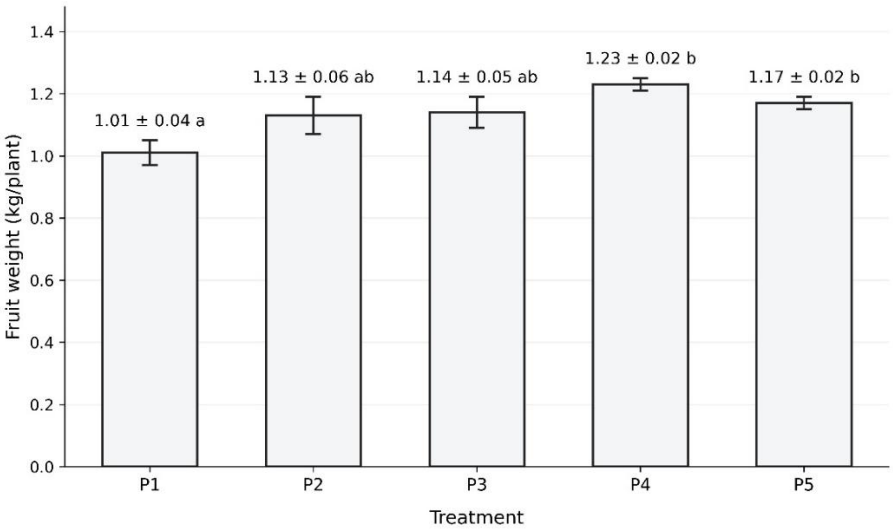


Fig. 2. Effect of M-Bio biofertilizer on fruit weight of melon grown in an NFT hydroponic system. P1 = 0 mL/L; P2 = 5 mL/L; P3 = 10 mL/L; P4 = 15 mL/L; and P5 = 20 mL/L M-Bio. Values are presented as mean ± standard error (SE). Different lowercase letters indicate significant differences among treatments according to Duncan's Multiple Range Test (DMRT) at $p < 0.05$.

This enhancement in fruit weight suggests that M-Bio effectively improves the overall physiological efficiency of the crop. Nitrogen-fixing microbes within the biofertilizer increase nitrogen availability, an essential element for the protein synthesis and enzymatic activities that drive fruit development. Concurrently, phosphate-solubilizing bacteria enhance the bioavailability of phosphorus, a crucial nutrient for ATP-mediated energy transfer and the accumulation of carbohydrates allocated to the developing Furthermore, plant growth-promoting microorganisms can influence plant development through phytohormone production and improved nutrient acquisition, potentially supporting fruit development and biomass accumulation (Backer et al., 2018; Timofeeva et al., 2023)..

Yield components

The application of M-Bio biofertilizer significantly influenced fruit quality attributes and harvest time (Table 2). Total soluble solids (°Brix), an indicator of fruit sugar content, increased alongside M-Bio concentrations up to 15 mL/L. The control treatment (P1) recorded a baseline value of 13.63 ± 0.22 °Brix, whereas the P4 treatment (15 mL/L) achieved the highest concentration at 15.15 ± 0.13 °Brix, marking a statistically significant increase over the control. The increased °Brix values observed following M-Bio application suggest an improvement in fruit soluble solids content, potentially associated with enhanced nutrient assimilation and physiological processes involved in fruit development. Similar improvements in horticultural crop quality following microbial biostimulant application have been reported by Melini et al. (2023). . Previous research confirms that biofertilizers containing phytohormone-producing microbes can stimulate plant metabolism and elevate quality traits such as sugar content (Duan et al., 2021). However, at the highest concentration (P5 = 20 mL/L), the °Brix value declined to 13.80 ± 0.11 °Brix, demonstrating that excessive application rates do not confer additional benefits to fruit quality.

Table 2. Effect of M-Bio concentration on yield components.

Treatment	Concentration	Brix (°Bx)	Fruit thickness (mm)	Harvest maturity (DAP)
P1	0 mL/L M-Bio	13.63 ± 0.22 a	31.33 ± 0.63 a	75.13 ± 0.78 b
P2	5 mL/L M-Bio	14.03 ± 0.06 ab	32.95 ± 0.97 ab	74.06 ± 0.84 b
P3	10 mL/L M-Bio	14.13 ± 0.14 b	35.96 ± 0.80 cd	73.44 ± 0.48 ab
P4	15 mL/L M-Bio	15.15 ± 0.13 c	38.22 ± 0.20 d	71.88 ± 0.13 a
P5	20 mL/L M-Bio	13.80 ± 0.11 ab	35.50 ± 1.28 bc	72.13 ± 0.07 a
F-0.05	3.056			
F-0.01	4.893			
Coefficient of variation		2.03%	4.92%	1.53%
F-Value		17.122**	9.901**	5.861**

Notes: Mean values followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level. F-value > F-table at the 5% significance level indicates significantly different treatments (*), while F-value > F-table at the 1% significance level indicates highly significantly different treatments (**). Treatments with F-value lower than the F-table are considered not significantly different (ns).

Fruit flesh thickness also increased following the application of M-Bio. While the control group produced a mean fruit thickness of 31.33 ± 0.63 mm, the P4 treatment (15 mL/L) yielded a thickness of 38.22 ± 0.20 mm, which was significantly greater than both the control and the lower-dosage treatments. Fruit thickness is primarily governed by cell division and cellular enlargement. These physiological processes are highly responsive to nutrient availability and phytohormone activity, particularly the auxins and gibberellins synthesized by rhizosphere microbes (Bottini et al., 2004). Furthermore, the nitrogen-fixing and phosphate-solubilizing bacteria present in M-Bio enhance the bioavailability of the macronutrients required for robust fruit tissue development. These findings align with previous research demonstrating that microbial inoculants effectively improve morphological fruit quality, including flesh thickness (Alori and Babalola, 2018).

Furthermore, M-Bio applications significantly influenced the time required to reach harvest maturity. Control plants (P1) required 75.13 ± 0.78 days after planting (DAP) to reach harvest, whereas M-Bio treatments accelerated this process to 71.88–74.06 DAP. The P4 treatment (15 mL/L) resulted in the earliest harvest at 71.88 ± 0.13 DAP, representing a statistically significant reduction in crop duration compared to the control. This accelerated maturation is likely attributable to increased nutrient availability and the role of microbial phytohormones in stimulating flowering and fruit development (Timofeeva et al., 2023).

Fruit maturation is fundamentally linked to hormonal balance and metabolic efficiency, both of which are readily modulated by functional microbes. The microbial synthesis of phytohormones, particularly gibberellins and auxins, coupled with enhanced nutrient solubilization, stimulates early vegetative growth and hastens the transition to the reproductive stage (Bhavya et al., 2023; Capo et al., 2023). Consequently, biofertilizer inoculation can meaningfully reduce the time to harvest while maintaining, or even improving, final crop yield and fruit quality. Overall, these results indicate that applying 15 mL/L of M-Bio yields the optimal outcome across three primary parameters: maximizing °Brix, increasing fruit thickness, and minimizing the time to harvest. This demonstrates that M-Bio functions not solely as a nutrient provider, but as a potent biostimulant capable of significantly enhancing both fruit quality and harvest efficiency.

Nutrient uptake

Applying M-Bio biofertilizer within the NFT hydroponic system significantly influenced the plant uptake of macronutrients (N, P, and K) (Table 3). In the control treatment (P1 = 0 mL/L), the basal uptake of N, P, and K was 434.40 ± 37.80 mg/plant, 84.09 ± 6.78 mg/plant, and 110.18 ± 8.90 mg/plant, respectively. While applying M-Bio at lower concentrations (5 to 10 mL/L) did not yield a statistically significant increase in nutrient absorption, higher concentrations (15 to 20 mL/L) substantially enhanced macronutrient assimilation. The P5 treatment (20 mL/L) produced the highest overall uptake rates, with N reaching 675.47 ± 66.15 mg/plant, P reaching 138.53 ± 14.16 mg/plant, and K reaching 169.28 ± 15.03 mg/plant.

In NFT hydroponic systems, nutrients are delivered in an aqueous solution, facilitating rapid root absorption. Introducing the functional microbes present in M-Bio further enhances this nutrient availability through targeted biological mechanisms. Specifically, nitrogen-fixing bacteria supply supplementary nitrogen via biological fixation directly within the root zone submerged in the nutrient film. This localized fixation explains the significant increase in N assimilation observed in the P4 and P5 treatments. Nitrogen remains critical for hydroponically cultivated plants, serving as a fundamental component in protein and chlorophyll synthesis, which ultimately drives vegetative growth (Jones et al., 2025).

Table 3. Effect of treatments on N, P, and K uptake in plants.

Treatment	Concentration	N Uptake (mg/plant)	P Uptake (mg/plant)	K Uptake (mg/plant)
P1	0 mL/L M-Bio	434.40 ± 37.80 a	84.09 ± 6.78 b	110.18 ± 8.90 a
P2	5 mL/L M-Bio	477.01 ± 38.18 a	53.17 ± 6.47 ab	116.95 ± 8.23 a
P3	10 mL/L M-Bio	476.00 ± 44.06 a	49.76 ± 6.40 a	116.08 ± 10.94 a
P4	15 mL/L M-Bio	647.84 ± 75.45 b	126.91 ± 15.40 c	165.69 ± 17.08 b
P5	20 mL/L M-Bio	675.47 ± 66.15 b	138.53 ± 14.16 c	169.28 ± 15.03 b
F-0.05	3.056			
F-0.01	4.893			
Coefficient of variation		3.29%	6.00%	2.07%
F-Value		4.126*	110.503**	7.35**

Notes: Mean values followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level. F-value > F-table at the 5% significance level indicates significantly different treatments (*), while F-value > F-table at the 1% significance level indicates highly significantly different treatments (**). Treatments with F-value lower than the F-table are considered not significantly different (ns).

The increased P uptake at higher M-Bio concentrations indicates robust activity of phosphate-solubilizing bacteria within the nutrient solution. These microbes secrete organic acids and phosphatase enzymes that solubilize phosphate complexes, which frequently precipitate in hydroponic solutions, thereby increasing P bioavailability to the plants (Duan et al., 2021). Consequently, M-Bio helps mitigate the risk of phosphate imbalances, a common challenge in NFT systems caused by fluctuations in nutrient solution pH. Furthermore, the enhanced K uptake observed in the M-Bio treatments is highly critical for hydroponic cultivation. Potassium plays a vital role in maintaining osmotic balance, improving water use efficiency, and

facilitating the translocation of photosynthates to developing fruit. Because roots in NFT systems rely on a thin nutrient film and frequently experience fluctuating ion concentrations, the presence of beneficial microbes helps the plants optimize K absorption (Alori and Babalola, 2018). The significantly increased K uptake in the P4 and P5 treatments directly correlates with the higher fruit weights per plant shown in Fig. 2, suggesting that the microbial consortium in M-Bio improves functional potassium utilization in soilless environments.

Overall, these findings confirm that M-Bio effectively enhances nutrient uptake in NFT hydroponic systems, even though the specific microbial dynamics differ from those in conventional soil-based cultivation. The most favorable agronomic outcomes were achieved at a concentration of 15 mL/L (P4), which perfectly aligns with the observed improvements in stem diameter, fruit weight, and overall fruit quality. Although applying the highest concentration of 20 mL/L (P5) resulted in maximum nutrient absorption, it did not yield further enhancements in crop productivity. This plateau in yield is likely attributable to physiological saturation, as the plants reached their assimilation limits when exposed to excessive nutrient availability under highly controlled hydroponic conditions.

Correlations between parameters

The correlation analysis (Fig. 3) revealed a robust relationship between macronutrient (N, P, and K) uptake and both growth and yield attributes. Correlation coefficients ranged from 0.27 to 0.79 for nutrient uptake in relation to stem diameter, fruit weight, fruit thickness, and °Brix, with N and K uptake generally showing stronger associations than P uptake. Furthermore, nutrient uptake was negatively correlated with harvest age (r = −0.69 to −0.94), indicating that greater nutrient uptake was associated with earlier harvesting. These findings suggest that improved nutrient assimilation may contribute to better plant growth, fruit development, and earlier maturation under the NFT hydroponic system.

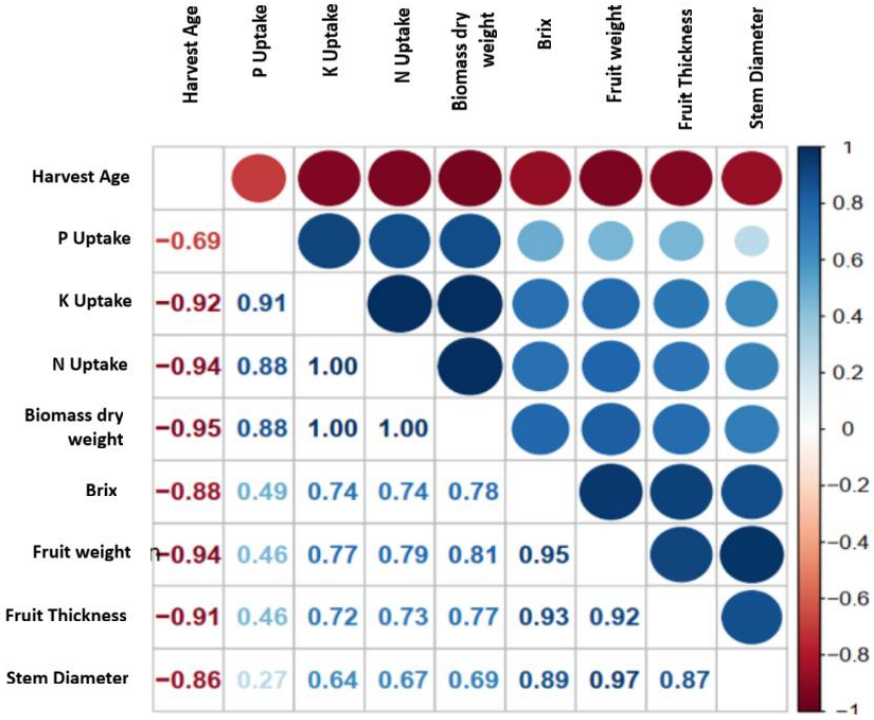


Fig. 3. Correlation heatmap illustrating the relationships among nutrient uptake (N, P, and K), vegetative growth, fruit characteristics, and harvest age in melon grown under an NFT hydroponic system. Blue circles indicate positive correlations, while red circles indicate negative correlations. Circle size and color intensity represent the strength of the correlation coefficients (r)..

This tight coupling between nutrient assimilation and crop yield highlights the pivotal role of M-Bio within hydroponic ecosystems. Although NFT systems supply dissolved nutrients, ionic imbalances and compound precipitation can still occur. The functional microbes in M-Bio, particularly nitrogen-fixing and phosphate-solubilizing bacteria, optimize nutrient availability and uptake efficiency despite the roots interacting with only a thin nutrient film. Their biological activity directly enhances photosynthesis, assimilate translocation, and fruit filling. These findings align with recent research demonstrating that microbe-based biofertilizers improve nutrient use efficiency in soilless environments by producing essential enzymes and secondary metabolites (Mejía-Guerra et al., 2025).

The consistent negative correlation between N, P, and K uptake and harvest time is a particularly noteworthy finding. This relationship suggests that the acceleration of the generative phase in hydroponic crops is driven not only by enhanced nutrient assimilation but also by the activity of functional microbes. The earlier harvesting observed in M-Bio-treated plants may be associated with improved nutrient availability and phytohormone-mediated regulation of plant development. Plant growth-promoting bacteria can produce or modulate phytohormones, including auxins, cytokinins, and gibberellins, which influence various physiological processes involved in plant growth and development (Backer et al., 2018; Timofeeva et al., 2024). However, further investigation is required to determine whether these mechanisms directly contributed to the shorter cultivation period observed in this study.. In the context of modern commercial agriculture, this reduced time to

harvest provides substantial agronomic advantages by enabling a higher cropping frequency within a given production cycle.

Materials and methods

Location and instrumentation

This study was conducted from May to September 2025, encompassing both field and laboratory components. The field experiment, which evaluated the growth and yield performance of the melons, was carried out at the experimental facility of the Faculty of Agriculture, Universitas Siliwangi. Subsequent laboratory analyses were performed at the Soil Science Laboratory at Universitas Siliwangi and the Integrated Research and Testing Laboratory (LPPT) at Universitas Gadjah Mada. Integrating these field and laboratory phases allowed for a comprehensive evaluation of the efficacy of foliar-applied M-Bio biofertilizer on the nutrient use efficiency (NUE) and crop yield of melons cultivated in a Nutrient Film Technique (NFT) hydroponic system. Key equipment and instrumentation utilized in this study included a standard NFT hydroponic setup, foliar sprayers, analytical digital balances, pH and electrical conductivity (pH/EC) meters, and drying ovens. Plant nutrient uptake was quantified using an atomic absorption spectrophotometer (AAS) or a UV-Vis spectrophotometer. Additionally, digital cameras were utilized for the comprehensive visual documentation of all experimental procedures.

Plant materials and manufacturer procedures of M-Bio fertilizer

The materials employed consisted of melon (*Cucumis melo* L.) seeds of Inthanon variety, foliar biofertilizer M-Bio, nutrient solution AB Mix, clean water, and growth media suitable for hydroponic seedling establishment. The M-Bio fertilizer used in this study was obtained from Insan Lestari, Tasikmalaya City. According to the manufacturer's formulation procedures, the fertilizer was produced using a microbial starter consortium consisting of *Azotobacter* sp., *Bacillus* sp., *Lactobacillus* sp., and *Saccharomyces* sp. The nutrient medium was prepared using molasses as the primary carbon source, supplemented with rice wash water and bean sprout extract to provide organic nutrients. During production, the base materials were prepared and mixed into a nutrient medium, which was subsequently sterilized. The microbial starter was then added to the sterile medium, and the mixture was fermented for a period of 7 to 21 days. Following fermentation, the liquid product was filtered and packaged for use.

M-Bio application and observation parameters

The study incorporated both analytical and experimental phases. Initially, the secondary metabolite profile of the M-Bio biofertilizer was characterized using Gas Chromatography–Mass Spectrometry (GC-MS). The greenhouse experiment employed a completely randomized design (CRD) comprising five foliar M-Bio concentration treatments: 0 mL/L (control), 5 mL/L, 10 mL/L, 15 mL/L, and 20 mL/L, with each treatment replicated four times. Seeds of the Inthanon melon variety were germinated in nursery trays, and the resulting seedlings were subsequently transplanted into an NFT hydroponic system installed within a greenhouse. While all plants received a continuous basal supply of standard AB Mix nutrient solution, foliar applications of M-Bio were administered at the designated treatment concentrations from the vegetative stage through to harvest.

During the cultivation period, fundamental growth variables, including plant height and leaf number, were regularly recorded. Leaf samples were collected periodically to analyze macronutrient uptake, specifically targeting nitrogen (N), phosphorus (P), and potassium (K) concentrations. At maturity, the evaluated yield and fruit quality parameters included total fruit number, individual and total fruit weight per plant, and total soluble solids (°Brix).

Statistical analysis

The collected data were analyzed using Analysis of Variance (ANOVA) to evaluate the significance of the treatment effects. When significant differences were detected, treatment means were compared using Duncan's Multiple Range Test (DMRT) at a 5% significance level. All statistical procedures were performed at a 95% confidence level.

Conclusion

In conclusion, this study demonstrates that foliar applications of M-Bio significantly increased stem diameter, fruit weight, total soluble solids (°Brix), and nutrient uptake in hydroponically grown melons, yielding optimal agronomic performance at a concentration of 15 mL/L. Furthermore, the M-Bio treatments stimulated early vegetative growth and reduced the time required to reach harvest. Applying the highest concentration (20 mL/L) yielded no additional enhancements in fruit yield or quality attributes. Overall, this research provides valuable insights into the efficacy of M-Bio foliar biofertilizers for optimizing the agronomic traits and nutrient assimilation of melons cultivated in NFT systems.

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