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Integrated Application of Arbuscular Mycorrhizal Fungi and NPK Fertilizer to Enhance Growth and Production of Tomato (*Solanum lycopersicum* L.)

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ABSTRACT

Tomato (*Solanum lycopersicum* L.) is an important horticultural crop with high economic and nutritional value, yet its cultivation is often sustained by intensive inorganic NPK fertilization that can degrade soil fertility and microbial diversity, motivating integrated nutrient management approaches such as arbuscular mycorrhizal fungi (AMF) inoculation. This study aimed to evaluate the combined effects of AMF and NPK fertilizer on tomato growth and production under greenhouse conditions. The experiment was conducted from April to July 2025 in Makassar, Indonesia, using F1 Servo tomato grown in 40 × 40 cm polybags containing a homogenized medium of topsoil, well-decomposed manure, and rice husk charcoal. A factorial randomized complete block design tested four AMF doses (0, 20, 30, 40 g polybag^{-1}) and four NPK doses (0, 5, 7.5, 10 g polybag^{-1}) with three replicates (16 combinations; 48 units). Data were analyzed by ANOVA, followed by DMRT at α = 0.05. AMF and NPK each significantly increased plant height at 12 weeks after planting, reaching 99.16 cm at 40 g AMF and 97.15 cm at 10 g NPK, with no interaction. Productive branches showed a significant interaction, peaking at 17.56 branches with 30 g AMF + 10 g NPK versus 10.33 in the unfertilized, non-inoculated control. Flowering age also responded synergistically, with 40 g AMF + 10 g NPK accelerating flowering to 39.56 days, whereas delayed flowering (46.56 days) occurred with 30 g AMF without NPK. Fruit number increased independently with AMF (up to 20.42 fruits plant^{-1}) and NPK (up to 20.92 fruits plant^{-1}), and fruit weight per plant rose with AMF (351.24 g at 40 g) and NPK (338.70 g at 10 g), without interaction. Individual fruit weight was not significantly affected, although the highest observed value was 19.54 g at 20 g AMF without NPK. Productivity reached 4.04 t ha^{-1} with 10 g NPK and increased to 4.84 t ha^{-1} under 40 g AMF + 10 g NPK, indicating that integrating AMF with NPK can improve key growth, phenology, and yield attributes relevant to more sustainable tomato nutrient management.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is a vital horticultural crop globally valued not only for its economic importance but also for its nutritional benefits, which include essential vitamins, minerals, antioxidants, and lycopene (Parmar et al., 2021). However, the sustainability of tomato cultivation is challenged by the widespread reliance on intensive use of inorganic fertilizers, particularly NPK formulations, which can lead to soil fertility decline, reduced microbial diversity, and environmental damage (Maurya et al., 2025). Consequently, integrated nutrient management (INM) strategies that combine microbial inoculants with mineral or organic nutrient sources are gaining attention as sustainable alternatives to conventional fertilization (Selim, 2020).

Role of Arbuscular Mycorrhizal Fungi (AMF) in Sustainable Tomato Cultivation Arbuscular mycorrhizal fungi form mutualistic associations with plant roots, effectively extending the root system's absorptive surface via fungal hyphae. This symbiosis enhances water and nutrient uptake, especially for less mobile nutrients like

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phosphorus (P), thus improving plant physiological performance (Salkić et al., 2025). In tomato, AMF inoculation has been reported to boost root growth, vegetative development, nutrient acquisition, drought tolerance, and overall productivity, while also reinforcing plant defenses against biotic and abiotic stresses (Orine et al., 2022).

Synergistic Effects of AMF and NPK Fertilizers in Tomato Production recent evidence highlights the benefits of combining AMF inoculation with mineral fertilizers in INM systems (Ullah et al., 2025). The combined application can significantly enhance nutrient-use efficiency-particularly P uptake-yield, and overall plant performance relative to fertilization alone. By integrating AMF, farmers may reduce their dependency on high doses of chemical fertilizers, thus promoting soil health and environmental sustainability without sacrificing yield (Qian et al., 2024).

For instance, a greenhouse study using indigenous AMF inoculum in tomato showed that applying AMF with 50% of the recommended NPK fertilizer dose resulted in significant increases in plant height, leaf and root biomass, nutrient uptake (Ca, K, Fe, Zn, P), and notably improved mycorrhizal colonization rates (100% frequency and 63% intensity) compared to non-inoculated controls (Chafai et al., 2023). Interestingly, tomato plants receiving 75% NPK in combination with AMF produced yields comparable to those fertilized at 100%, suggesting that the presence of AMF allows for fertilizer reduction without yield penalties. Furthermore, AMF inoculation enhanced fruit quality, increasing Brix index (a sweetness indicator) and total carotenoid content, which are valuable attributes for human nutrition and market value (Edina et al., 2025)

Similar trends are reported under field conditions where inoculation enhanced nutrient uptake (P, K, Ca, Mg), fruit yield, mycorrhizal root colonization, and economic returns when integrated with organic amendments and NPK fertilizers (Bernados et al., 2024). The positive correlation between AMF colonization and nutrient uptake highlights the biological mechanism through which AMF enhance tomato productivity.

Influence of Tomato Genotype and Environmental Factors Variation among tomato cultivars in response to AMF has been documented, suggesting that genotype compatibility influences the success of inoculation. For example, in a study comparing two cultivars, Better Boy outperformed Roma in growth, nutrient uptake, physiological traits, yield, and fruit quality upon mycorrhizal inoculation, with root colonization rates varying significantly among AMF strains (Ullah et al., 2023). This genotype-specific response underscores the necessity of locally adapted evaluations for optimizing AMF use.

Environmental factors such as soil properties, irrigation management, and local inoculation methods affect the effectiveness of the AMF-NPK interaction, necessitating site-specific approaches for best results (Habtemariam et al., 2026).

Broader Insights from Related Crops and Systems While direct studies on tomato provide robust evidence supporting AMF and NPK integration, related research in other crops points toward consistent beneficial outcomes. For example, in maize, indigenous AMF combined with only 50% of the full NPK dose enhanced growth, tissue nutrient content, and yield, supporting the potential to halve fertilizer use while improving soil nutrient availability (Fall et al., 2023). Likewise, in rice, AMF inoculation mitigated yield losses due to water stress and low fertilization, highlighting AMF's role in resilience and nutrient use efficiency (Mbodj et al., 2025).

This integrated approach not only maintains high productivity, but also contributes to soil fertility preservation and environmental sustainability. However, varying effectiveness depending on genotype, soil and local climate conditions, as well as management practices, necessitates localized experimentation and optimization(Bekunda et al., 2022). The objective of this study to evaluate the combined effects of AMF and NPK fertilization on tomato growth and yield is closely aligned with current literature, which indicates that AMF can reduce dependence on fertilizers and significantly enhance plant performance. These findings are expected to serve as a reference for sustainable nutrient management practices that balance productivity with ecological management

MATERIALS AND METHODS

This study was conducted from April to July 2025 in the greenhouse of the Faculty of Agriculture, Universitas Muslim Indonesia, Makassar, Indonesia. The experiment was carried out under controlled greenhouse conditions to minimize the influence of external climatic variability during plant growth and development.

The plant material used in this study was F1 Servo tomato seed (*Solanum lycopersicum* L.). Other materials included arbuscular mycorrhizal fungi (AMF) inoculum, compound NPK fertilizer, well-decomposed manure, topsoil, rice husk charcoal, labels, raffia rope, and water. The growing medium consisted of a mixture of soil, manure, and rice husk charcoal in suitable proportions to support optimal plant growth. All media components were homogenized before being placed into 40 × 40 cm polybags.

1. **Experimental Design and Treatments**

The experiment was arranged using a factorial Randomized Complete Block Design (RCBD) consisting of two treatment factors. The first factor was the application of arbuscular mycorrhizal fungi (AMF) with four treatment levels:

M0 = without AMF inoculation (control),
M1 = 20 g AMF polybag^{-1},
M2 = 30 g AMF polybag^{-1}, and
M3 = 40 g AMF polybag^{-1}.

The second factor was the application of NPK fertilizer with four treatment levels:
N0 = without NPK fertilizer (control),
N1 = 5 g polybag^{-1},
N2 = 7.5 g polybag^{-1},
N3 = 10 g polybag^{-1}.

Each treatment combination was replicated three times, resulting in 16 treatment combinations and a total of 48 experimental units.

2. **Data Analysis**

The observed data were analyzed using analysis of variance (ANOVA) based on the factorial RCBD model to determine the effects of AMF inoculation, NPK fertilizer application, and their interaction on tomato growth and production. When the ANOVA indicated significant differences at the 5% significance level, mean comparisons were further analyzed using Duncan's Multiple Range Test (DMRT) at α = 0.05. All statistical analyses were performed using Microsoft Excel software.

RESULTS AND DISCUSSION

1. **Plant Height**

The results of observations and analysis of variance showed that the provision of mycorrhiza and NPK fertilizer had a very significant effect, while the interaction between mycorrhiza and NPK fertilizer did not have a significant effect on the height of tomato plants.

Table 1. The Average plant height (cm) of tomatoes at 12 weeks after planting when given mycorrhiza and NPK fertilizer

Mycorrhiza	NPK				Average
	N0	N1	N2	N3	
M0	76.80	83.64	85.51	86.55	83.13^{c}
M1	85.66	93.66	90.34	94.08	90.93^{b}
M2	92.16	95.83	97.99	106.33	98.08^{a}
M3	95.03	98.59	101.36	101.68	99.16^{a}
Average	87.41^{b}	92.93^{a}	93.80^{a}	97.16^{a}	
DMRT			4.25		

Note: Numbers followed by different letters in the same row (a,b,c) and column (x,y,z) are significantly different at the 0.05% DMRT test level.

The results of the 5% DMRT test in Table 1 show that the best average tomato plant height was 99.16 cm when given 40 g of mycorrhiza per polybag (M3), significantly different from the control and 20 g/polybag treatments, but not significantly different from the 30 g/polybag treatment. The lowest average plant height was 83.13 cm when given the control treatment without mycorrhiza.

The best average plant height was 97.15 cm when given 10 g of NPK fertilizer per polybag, which was not significantly different from the 7.5 g/polybag and 5 g of NPK fertilizer treatments, but significantly different from the control treatment without NPK fertilizer. The lowest average plant height was 87.41 cm when given the control treatment without mycorrhiza.

The results of the 5% DMRT test for tomato plant height demonstrate clear effects of both mycorrhiza application and NPK fertilizer dosage on plant growth. Specifically, the application of 40 g mycorrhiza per polybag (M3) yielded the highest average plant height of 99.16 cm. This value was significantly greater than that of the control group (no mycorrhiza) and the 20 g per polybag treatment, indicating a positive growth-promoting effect of mycorrhizal inoculation at higher doses. However, the 40 g dose was not significantly different from the 30 g per polybag treatment, suggesting a plateau in benefit between these two higher mycorrhiza application rates. In contrast, the control treatment without mycorrhiza had the lowest average height at 83.13 cm, highlighting the substantial benefit conferred by mycorrhizal fungi on tomato plant height under the experimental conditions (Sipayung et al., 2024).

Similarly, NPK fertilizer significantly influenced plant height. The best average height recorded with NPK was 97.15 cm at the dose of 10 g per polybag. This height was not significantly different from those obtained with 7.5 g and 5 g NPK, illustrating that relatively low to moderate fertilizer doses similarly promote growth without statistically distinguishable differences. The 10 g dose was, however, significantly different from the control treatment without NPK, which showed the lowest average height of 87.41 cm, confirming the essential role of NPK nutrients in supporting tomato plant development (Adeyeye et al., 2025).

These findings collectively emphasize that both mycorrhiza and NPK fertilizer enhance tomato plant height relative to untreated controls, with optimal growth observed at intermediate to higher doses of mycorrhiza (30–40 g/polybag) and moderate doses of NPK fertilizer (5–10 g/polybag). The statistically significant increases caused by these treatments align with broader evidence that mycorrhizal fungi symbiotically improve nutrient uptake and growth in tomatoes, as documented in studies demonstrating improved growth parameters with mycorrhizal inoculation (Hegedűsová et al., 2016). Likewise, balanced fertilization regimes including NPK are crucial to achieving optimal growth, as underscored by various investigations into fertilizer management in solanaceous crops (M Hashesh et al., 2024).

Furthermore, the synergy of mycorrhizal inoculation and nutrient management potentially contributes to enhanced physiological and biochemical functions, leading to improved plant performance even under stress conditions (Alam et al., 2022). The documented increase in plant height presented here supports the integration of microbial inoculants and nutrient optimization in tomato cultivation to maximize vegetative growth (Carballo-Sánchez et al., 2026).

2. Number of productive branches

The results of observations and analysis of variance showed that the provision of mycorrhiza and NPK fertilizer had a very significant effect, while the interaction between mycorrhiza and NPK fertilizer had a significant effect on the number of productive branches of tomato plants.

Table 2. The Average number of productive branches of tomatoes aged 12 weeks after planting when given mycorrhiza and NPK fertilizer

Mycorrhiza	NPK				Average
	N0	N1	N2	N3	
M0	10.33^{b}_{y}	12.33^{ab}_{y}	13.56^{a}_{xy}	11.89^{ab}_{z}	12.03
M1	13.22^{a}_{x}	13.11^{a}_{y}	12.34^{a}_{y}	13.11^{a}_{yz}	12.95
M2	12.67^{b}_{x}	14.55^{b}_{x}	13.67^{b}_{xy}	17.56^{a}_{x}	14.61
M3	14.00^{a}_{x}	15.33^{a}_{x}	14.89^{a}_{x}	15.22^{a}_{y}	14.86
Average	12.56	13.83	13.61	14.44	
DMRT	2.13				

Note: Numbers followed by different letters in the same row (a,b,c) and column (x,y,z) are significantly different at the 0.05% DMRT test level.

The results presented in Table 2 of the referenced study demonstrate the significant interactive effects of mycorrhizal inoculation and NPK fertilization on the number of productive branches in tomato plants. Specifically, the highest average number of productive branches, 17.56, was observed in the treatment combining 30 g of mycorrhiza per polybag (M2) with 10 g of NPK fertilizer per polybag (N3). This outcome was significantly different from other treatment combinations, except for those involving M3N0, M3N1, M3N2, and M1N0, indicating these treatments yielded statistically comparable branch numbers. Conversely, the lowest average number of productive branches, 10.33, occurred in the control treatment with no mycorrhiza and no NPK fertilizer applied.

These findings align with a broader body of research illustrating that arbuscular mycorrhizal fungi (AMF), when applied in conjunction with balanced fertilization regimes, enhance tomato plant growth parameters, including branching, yield, and nutrient uptake. Multiple studies have confirmed that AMF inoculation improves nutrient acquisition, particularly phosphorus, and positively influences physiological and morphological traits in tomatoes, thereby facilitating higher productivity (Felföldi et al., 2022).

Specifically, the synergy between moderate mycorrhizal inoculum doses and optimal NPK fertilizer levels enhances nutrient absorption and growth vigor. For example, tomato plants inoculated with AMF and treated with about 50-75% of recommended fertilizer doses demonstrated superior growth and yield comparable or better than full NPK application alone, reflecting both resource-use efficiency and reduced chemical inputs (Salkić et al., 2025). The observed highest number of productive branches in the M2N3 treatment is consistent with this pattern, suggesting that the inoculated fungi enhance nutrient uptake from NPK and possibly other soil nutrients, thus stimulating branching development (Chaudhary et al., 2024).

The treatments M3N0, M3N1, M3N2, and M1N0, which did not differ significantly from M2N3 in branch number, likely involve comparable effective levels of either fungal inoculum or baseline fertilization promoting plant branching. This highlights the complexity of interactions where both quantity of mycorrhizal inoculum and fertilizer rates influence growth outcomes. It also underscores the potential for reducing fertilizer doses when supplemented by mycorrhizal inoculation without sacrificing key growth traits (Prettl et al., 2024).

Conversely, the lowest branch number in no-mycorrhiza and no-fertilizer treatments reinforces the importance of either nutrient supplementation or beneficial microbial inoculation for optimal plant architectural development. AMF enhances root absorptive capacity, water relations, and mineral uptake, ultimately supporting the formation of productive branches under adequate nutrient

3. Flowering age

The results of observations on the flowering age of tomato plants with the provision of mycorrhiza and NPK fertilizer are presented in Tables 3a and 3b. Analysis of variance shows that the provision of mycorrhiza and NPK fertilizer has a very significant effect, while the interaction between mycorrhiza and NPK fertilizer has a significant effect on the flowering age of tomato plants.

Table 3. The average age of tomato flowering is 12 weeks after planting when given mycorrhiza and NPK fertilizer.

Mycorrhiza	NPK				Average
	N0	N1	N2	N3	
M0	45.11 $^{a}_{xy}$	44.56 $^{ab}_{x}$	42.00$^{b}_{x}$	46.00 $^{a}_{x}$	44.42
M1	43.89 $^{a}_{xy}$	42.11 $^{ab}_{x}$	42.33 $^{a}_{x}$	43.11 $^{a}_{y}$	42.86
M2	46.56 $^{a}_{x}$	42.00$^{b}_{x}$	41.78$^{b}_{x}$	41.33 $^{b}_{yz}$	42.92
M3	43.66 $^{a}_{y}$	43.11 $^{a}_{x}$	41.56 $^{a}_{x}$	39.56 $^{b}_{yz}$	41.97
Average	44.81	42.95	41.92	42.50	
DMRT	2.70				

Note: Numbers followed by different letters in the same row (a,b,c) and column (x,y,z) are significantly different at the 0.05% DMRT test level.

The results of the 5% DMRT test as summarized in Table 3 reveal a significant interaction effect between arbuscular mycorrhizal fungi (AMF) inoculation rates and NPK fertilization levels on the average flowering age of tomato plants. Specifically, the treatment combination of 40 g of mycorrhiza per polybag (M3) and 10 g of NPK per polybag (N3) produced the fastest average flowering age of 39.56 days, which was significantly earlier than all other treatment combinations tested. This outcome highlights the synergistic effect of high AMF inoculation levels combined with adequate NPK fertilization in accelerating the flowering phase of tomato plants.

In contrast, the treatment consisting of 30 g of mycorrhiza per polybag (M2) without any NPK fertilization (A0) resulted in the longest average flowering age of 46.56 days. This indicates that the absence of NPK fertilization, even with moderate mycorrhizal inoculation, delays tomato flowering compared to treatments with sufficient nutrient supplementation.

These findings align with the broader literature wherein AMF inoculation enhances nutrient uptake efficiency, including phosphorus and other essential minerals, thereby enabling earlier developmental transitions such as flowering (Singh et al., 2024). The improvement is particularly notable when AMF symbiosis is combined with appropriate NPK fertilization, which likely supports optimal plant growth conditions.(Razack et al., 2024)

The reduced flowering time under combined AMF and NPK treatment might be attributed to enhanced nutrient acquisition and improved physiological status of the plants. AMF symbiosis is known to promote nutrient uptake and improve drought tolerance and stress resilience, thereby fostering overall plant vigor and earlier flowering (Boutasknit et al., 2024; Soussani et al., 2023).

Therefore, the significant difference in flowering age between the M3N3 treatment and less intensively fertilized or unfertilized treatments underscores the interactive benefits of integrating biological inocula such as AMF with chemical fertilization to optimize tomato crop phenology and productivity.(Edina et al., 2025)

In summary, the study demonstrates that the fastest average flowering age in tomato occurs with a synergistic interaction of 40 g mycorrhiza/polybag plus 10 g NPK/polybag. Conversely, the lack of NPK fertilization, even with moderate mycorrhizal inoculation, leads to delayed flowering. This supports the strategy of integrated nutrient management combining microbial inoculants and reduced chemical fertilizer doses for improved crop performance (Chafai et al., 2023; Felföldi et al., 2022).

4. Number of Fruits/plant

The results Observations and analysis of variance showed that mycorrhizal application had a significant effect, while NPK fertilizer had a very significant effect. However, the interaction between mycorrhizal and NPK fertilizer had no significant effect on the number of fruits per tomato plant.

Table 4. Average number of fruits per tomato plant with mycorrhizal and NPK fertilizer applications

Mycorrhiza	NPK				Average
	N0	N1	N2	N3	
M0	16.33	18.33	19.33	20.00	18.50^{b}
M1	19.00	19.00	20.33	20.67	19.75^{ab}
M2	19.33	20.33	20.67	21.00	20.33^{a}
M3	19.33	20.33	20.00	22.00	20.42^{a}
Average	18.50^{b}	19.50^{ab}	20.08^{a}	20.92^{a}	
DMRT	1,53				

Note : Numbers followed by different letters in the same row (a,b,c) and column (x,y,z) are significantly different at the 0.05% DMRT test level.

The summary you provided regarding the 5% DMRT test results on the number of fruits per tomato plant reflects key findings from research involving the effects of mycorrhizal inoculation and NPK fertilizer treatments on tomato yield.

Specifically, the best average fruit number per plant, 20.42 fruits, was observed with an application of 40 g of mycorrhiza per polybag (M3). Interestingly, this result was statistically comparable to the treatments with 30 g and 20 g of mycorrhiza per polybag, indicating that these three dosages similarly enhanced fruit production, while all were significantly better than the non-mycorrhizal control, where the lowest average fruit number of 18.50 was recorded. This suggests a clear positive influence from mycorrhizal inoculation on tomato fruit yield, as the symbiotic relationship improves nutrient uptake and plant growth, corroborating established benefits of arbuscular mycorrhizal fungi (AMF) inoculation in tomatoes (Chafai et al., 2023; Felföldi et al., 2022).

Similarly, the application of NPK fertilizer also showed significant effects. The best average number of fruits per plant, 20.92 fruits, was achieved with 10 g of NPK fertilizer per polybag. This was not significantly different from when 7.5 g or 5 g of NPK was applied, but significantly outperformed the non-mycorrhizal control with 18.50 fruits per plant. This pattern illustrates that moderate NPK fertilization improves fruit yield effectively compared to no fertilization, aligning with findings about chemical fertilizer applications enhancing tomato yield components such as plant height, stems, leaves, and fruit number across tomato varieties (Felföldi et al., 2022; Maxotova et al., 2021).

The significant difference between treatment groups and the control highlights the critical role both mycorrhizal inoculation and fertilization play in optimizing tomato production. The non-mycorrhizal/control treatment consistently resulted in the lowest fruit counts, underlining the importance of symbiotic fungi and adequate nutrient supply for maximizing yield.

Moreover, studies have demonstrated that mycorrhizal colonization enhances nutrient uptake especially phosphorus, potassium, and micronutrients-leading to improved tomato growth and yield parameters. For example, combining mycorrhizal inoculation with reduced rates (50–75%) of recommended chemical fertilizers can achieve yields not significantly lower than full fertilizer dosages, while enhancing fruit quality indices like Brix and carotenoids (Chafai et al., 2023). This integrated nutrient management approach supports sustainable agriculture by potentially reducing chemical fertilizer dependence without sacrificing yield.

The comparative 5% DMRT test results in Table 4 clearly indicate that both mycorrhizal inoculation at 20–40 g per polybag and NPK fertilization at 5–10 g per polybag significantly improve the average number of fruits per tomato plant over the non-mycorrhizal control. These findings are consistent with broader research demonstrating that both biological inoculants (AMF) and chemical nutrients (NPK) play complementary and beneficial roles in enhancing tomato production under controlled conditions ((Chafai et al., 2023; Felföldi et al., 2022; Maxotova et al., 2021).

5. Fruit Weight/Plant

The results Observations and analysis of variance (ANOVA) showed that the application of mycorrhizae and NPK fertilizer had a highly significant effect, while the interaction between mycorrhizae and NPK fertilizer had no significant effect on fruit weight per tomato plant.

Table 5. Average Fruit Weight per Tomato Plant (g) in the Mycorrhizae and NPK Fertilizer Applications

Mycorrhiza	NPK				Average
	N0	N1	N2	N3	
M0	270.83	293.17	297.67	292.65	288.58^{b}
M1	315.40	320.59	311.96	324.69	318.16^{ab}
M2	280.69	343.27	325.86	323.56	318.34^{ab}
M3	311.82	321.58	357.65	413.92	351.24^{a}
Average	294.68^{b}	319.65^{ab}	323.28^{ab}	338.70^{a}	
DMRT	41.62				

Note: Numbers followed by different letters in the same row (a, b, c) and column (x, y, z) are significantly different at the 0.05% DMRT test level.

The data you referenced regarding the 5% DMRT test in Table 5, showing variations in average fruit weight per tomato plant under different doses of mycorrhizae and NPK fertilizer, indicates several important findings consistent with the broader research on the effects of arbuscular mycorrhizal fungi (AMF) and fertilization on tomato yield.

Firstly, the highest average fruit weight achieved with 40 g mycorrhizae per polybag (351.24 g) not being significantly different from the 30 g and 20 g treatments, but significantly greater than the control without mycorrhizae (288.58 g), aligns well with the well-documented positive impact of AMF inoculation on tomato growth and productivity. AMF inoculation improves nutrient uptake, particularly of phosphorus, and enhances plant growth parameters including fruit yield and quality. Studies conducted under greenhouse and field conditions have consistently demonstrated that AMF inoculation leads to increased plant height, biomass, nutrient acquisition, and especially fruit yield compared to non-inoculated controls

(Boutasknit et al., 2024). For example, inoculated tomato plants showed significant increases in nutrient content and yield, partly due to improved root colonization by AMF and symbiotic enhancement of nutrient acquisition, which contributes to greater fruit weight.

Similarly, the findings regarding NPK fertilizer treatments where 10 g/polybag yielded the highest average fruit weight (338.70 g), significantly better than the control without NPK (294.68 g), but not statistically different from lower NPK doses, are consistent with observations that reduced but optimized levels of chemical fertilizers combined with AMF can sustain or increase yields. Research shows that applying chemical fertilizers at 50-75% of recommended doses in combination with AMF inoculation can produce yields comparable or superior to full doses of fertilizer alone, while also enhancing fruit quality attributes such as total carotenoids and sugar content (Brix index) (Trejo et al., 2021). This synergistic effect allows reduced fertilizer inputs, improving sustainability and reducing environmental impact without sacrificing productivity.

Furthermore, these results complement findings that AMF inoculation can partially substitute chemical fertilizers by improving soil nutrient availability and uptake efficiency. For instance, experiments with AMF combined with 50% NPK fertilizer were shown to significantly increase yield and nutrient content in other crops and tomato varieties, often demonstrating no significant difference from full NPK fertilization alone (Fall et al., 2023). This reinforces the pattern observed where the control (no mycorrhizae or fertilizer) consistently underperforms relative to treatments involving AMF and/or NPK fertilizers.

In conclusion, the reported fruit weight data with varying mycorrhizal and NPK doses reflect the important role of AMF as a biostimulant that enhances tomato productivity. The highest fruit weights obtained with moderate to high doses of mycorrhizae or NPK fertilizer significantly exceed the control treatments, confirming that inoculation and optimized fertilization substantially improve yield outcomes. These results support an integrated nutrient management approach, combining mycorrhizal inoculation with reduced chemical fertilizer application to achieve enhanced tomato growth, yield, and sustainability (Kakabouki et al., 2024)

6. Fruit Weight/Fruit

The results Observations and analysis of variance (ANOVA) showed that the application of mycorrhizae and NPK fertilizer, as well as the interaction between mycorrhizae and NPK fertilizer, did not significantly affect the fruit weight per tomato plant.

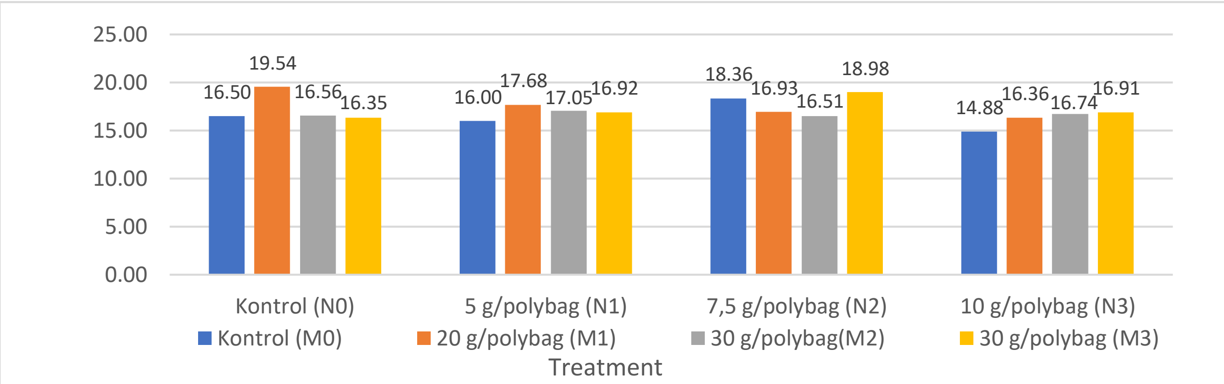

Figure 1. Average fruit weight per fruit with mycorrhizae and NPK fertilizer.

The observation from Figure 1 that applying 20 g mycorrhizae per polybag without NPK fertilizer (M1N0) resulted in a relatively high average fruit weight per fruit (19.54 g), compared to the lowest average in the control without mycorrhizae but with 10 g NPK (M0N3) at 14.88 g, aligns with documented trends in the literature regarding the impacts of arbuscular mycorrhizal fungi (AMF) and fertilization on tomato fruit development.

Although the figure indicates no statistically significant effects on fruit weight per individual tomato fruit when combining mycorrhizae and NPK fertilizer, the trend of improved fruit weight with AMF inoculation alone corresponds to evidence that AMF enhance nutrient uptake, growth, and yield parameters in tomatoes. AMF symbiosis enhances the plant's ability to absorb phosphorus and other minerals, which in turn supports better fruit development even in the absence of chemical fertilizers (Felföldi et al., 2022). Notably, these fungi create a mutualistic relationship that improves nutrient exchange and water uptake, fostering greater fruit biomass.

The lower fruit weight in the treatment without mycorrhizae but with NPK fertilizer suggests that nutrient input alone may not fully substitute benefits provided by AMF inoculation. This supports the notion that chemical fertilization and mycorrhizal symbiosis can act complementarily rather than interchangeably. Integrated nutrient management practices combining AMF inoculation with reduced fertilizer doses have shown potential to optimize yield and quality, reduce fertilizer dependency, and improve environmental sustainability (Bernados et al., 2024; Fall et al., 2023).

Further experimental reports describe that while mycorrhizal inoculation may not always produce statistically significant differences in fruit weight per fruit, it typically leads to enhanced fruit quality traits such as increased sugar content (Brix), carotenoid concentration, and nutrient uptake, contributing to improved overall fruit quality and marketability (Chafai et al., 2023; Fusco et al., 2022). The positive effects on physiological and quality attributes may not always directly translate to significant increases in individual fruit weight in every trial but indicate beneficial impacts on plant health and productivity.

the trend observed in Figure 1 regarding fruit weight per fruit corroborates the broader understanding that AMF inoculation positively influences tomato fruit development and quality, even in the absence of chemical fertilization. Although the application of NPK fertilizer can boost growth, the absence of mycorrhizae limits the maximum potential fruit weight, indicating that mycorrhizal symbiosis and nutrient fertilization together form an effective strategy for improving tomato fruit production and quality (Bernados et al., 2024; Chafai et al., 2023; Felföldi et al., 2022).

CONCLUSIONS

Both AMF and NPK treatments independently improved several growth and yield parameters in the plants. AMF40 notably increased plant height to 99.16 cm at 12 weeks after planting. A significant interaction between AMF and NPK was observed in the number of productive branches, with the M2N3 treatment producing 17.56 branches compared to 10.33 in the control. Flowering time showed a synergistic reduction under the combined AMF40+NPK10 treatment, reaching the earliest flowering at 39.56 days. While both AMF and NPK individually increased the number of fruits per plant (up to 20.42 and 20.92 fruits, respectively), no interaction effect was detected for this trait. Fruit weight per plant was also enhanced independently by AMF (351.24 g at 40 g) and NPK (338.70 g at 10 g), although individual fruit weight was not significantly affected by treatments. The highest productivity was achieved with the combined AMF40+NPK10 treatment at 4.84 t/ha, surpassing the 4.04 t/ha recorded with NPK10 alone.

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