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Natural biostimulants in sustainable agriculture: Effects of *Moringa* and *Acacia* extracts on tomato yield and photosynthesis

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ABSTRACT

Tomato (*Solanum lycopersicum* L.) is a globally important vegetable crop, and sustainable strategies to enhance its growth and yield are of increasing interest. This study investigated the effects of foliar applications of *Moringa oleifera* (M) and *Acacia nilotica* (A) leaf extracts, individually and in combination, at different concentrations (0, 10, 15, and 20 ml L^{-1}) on growth, photosynthetic performance, and fruit yield of tomato seedlings. A factorial experiment was conducted under greenhouse conditions in a completely randomized block design with three replications. Results showed that the combined application of M (15 ml L^{-1}) + A (20 ml L^{-1}) and M (20 ml L^{-1}) significantly enhanced plant growth, photosynthetic indices (Fv/Fm, PI, SPAD, CO_2 assimilation rate, stomatal conductance, and intercellular CO_2 concentration), and fruit yield compared to individual treatments and the control. Moderate to high concentrations of the extracts produced the most pronounced effects, while excessive concentrations sometimes led to inhibitory responses. The findings suggest that the synergistic use of *Moringa* and *Acacia* extracts can effectively improve tomato performance by enhancing photosynthetic efficiency and assimilate translocation, providing a sustainable alternative to conventional chemical fertilizers.

Highlights

- Moringa and Acacia extracts significantly increased greenhouse tomato yield.
- Maximized Fv/Fm, transpiration, and yield under combined M15+A20 treatment.
- Inhibited photosystem II performance and PI at excessive extract concentrations.

1. Introduction

Tomato (*Solanum lycopersicum* L., Solanales: Solanaceae) is recognized as one of the world's most important vegetable crops. It is grown on about 5.17 million hectares worldwide, producing roughly 189 million tons annually, with an average yield of 36.6 tons per hectare (FAO, 2021). Tomatoes are extensively utilized both fresh and processed due to their abundance of vital nutrients and bioactive compounds that contribute to human health (Karačić et al., 2024). Despite the continuous rise in global tomato demand, many producers have become increasingly dependent on chemical fertilizers, which has led to notable environmental and economic challenges (Zhang et al., 2024). The excessive application of nitrogen fertilizers is particularly problematic, as it contributes to groundwater contamination and elevated emissions of greenhouse gases (Zhou et al., 2022). In response, research efforts have shifted toward more sustainable strategies, emphasizing the potential of plant-derived extracts and essential oils as natural biostimulants. These bio-based inputs not only enhance plant growth, nutrient assimilation, and fruit quality but also provide an effective means to reduce reliance on conventional chemical fertilizers (Rajabi Hamedani et al., 2020).

A growing body of evidence supports the positive role of plant extracts and essential oils in promoting plant growth and productivity. In tomatoes, the foliar application of plant extracts has been shown to enhance both vegetative

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growth and fruit yield (Khalf and Khaleel, 2022; Mbuyisa et al., 2023).

Similarly, the exogenous use of botanical extracts significantly improved growth performance and physiological traits in potato plants (Khalf and Khaleel, 2022).

Jang and Kuk (2019) also demonstrated that the application of various plant-derived extracts enhanced lettuce biomass accumulation and yield attributes. In another study, Souri and Bakhtiarizade (2019) reported that rosemary extract application facilitated nutrient uptake and improved overall growth quality in tomato seedlings.

Despite these beneficial outcomes, some reports have indicated potential phytotoxic effects associated with certain commercial essential oils, such as those observed in cucumber plants, suggesting that the efficacy of these bioactive compounds strongly depends on their type and concentration (Ibáñez and Blázquez, 2020). More recent investigations have highlighted that extracts obtained from peppermint (*Mentha piperita*), thyme (*Zataria multiflora*), and savory (*Satureja hortensis*) have a positive influence on physiological and growth-related parameters in tuberose (*Polianthes tuberosa*), representing promising natural alternatives to synthetic agrochemicals (Babarabie and Zarei, 2024). Collectively, these findings indicate that plant extracts act as efficient biostimulants capable of enhancing plant metabolism, growth, and yield, thereby contributing to sustainable crop production systems.

Moringa (*Moringa oleifera*), recognized for its notable nutritional and medicinal properties, has recently garnered considerable attention in the context of sustainable agriculture. Leaf extracts of *Moringa* are rich in bioactive compounds such as cytokinins, flavonoids, and antioxidants, which can function as natural growth stimulants. (Pareek et al., 2023).

Acacia nilotica (L.), a medium-sized tree of the Mimosaceae family, is native to tropical and subtropical regions and is widely recognized for its medicinal and agronomic significance. Beyond its traditional medicinal uses, recent studies have highlighted the potential of A. nilotica leaf extracts as natural biostimulants capable of promoting plant growth (Revathi et al., 2024).

Foliar or seed applications of aqueous and ethanolic leaf extracts have been shown to enhance seed germination and early seedling development, indicating their value in improving crop performance and supporting sustainable agricultural practices (Manshad et al, 2023).

Despite extensive research on the use of plant extracts as natural growth stimulants, limited information is available on the combined effects of *Moringa oleifera* and *Acacia nilotica* leaf extracts on growth, photosynthesis, and fruit yield of tomato at different concentrations, as previous studies have primarily focused on the individual effects of each extract, and the precise mechanisms underlying their combined influence on physiological and performance-related traits remain largely unexplored. Therefore, the main aim of this study was to investigate the effects of combined applications of *Moringa* and *Acacia* extracts at varying concentrations on tomato growth and photosynthetic performance for maximizing plant productivity.

It is hypothesized that the simultaneous application of *Moringa* and *Acacia* extracts can significantly enhance plant growth and yield. The novelty and contribution of this research lie in the systematic evaluation of the combined effects of *Moringa* and *Acacia* extracts, the identification of an optimal natural and sustainable alternative to chemical fertilizers, and the provision of insights that support sustainable agriculture and lay the foundation for future studies on other crops.

2. Materials and methods

2.1. Experimental site and treatments

The experiment was conducted in 2024 in the greenhouse of Hormozgan University using a factorial arrangement within a completely randomized block design (CRBD) with three replications. Plants were grown in a greenhouse under day/night temperatures of 26 ± 2/18 ± 2°C, a relative humidity of 65 ± 5%, and an 11-h light/13-h dark photoperiod.

Uniform tomato seedlings were transplanted into pots containing a mixture of cocopeat and perlite. One seedling was planted in each pot. Each treatment consisted of three replicates, with three pots per replicate (a total of nine plants per treatment).

Data obtained from the three plants within each replicate were averaged before statistical analysis. Immediately after transplanting, humic acid was applied to the seedlings to reduce transplanting stress and to promote root establishment in the new growth medium.

The experimental treatments consisted of foliar applications of leaf extracts from *Acacia nilotica* (A) and *Moringa oleifera* (M) at four concentrations (0, 10, 15, and 20 ml L^{-1}), with distilled water serving as the control. Foliar spraying was performed three times at 10-day intervals, starting 10 days after transplantation. Seedlings were irrigated twice a week with Hoagland nutrient solution to provide optimal nutrition and maintain suitable growth conditions throughout the experiment.

2.2. Preparation of aqueous leaf extracts

Aqueous leaf extracts were obtained using a soaking approach. Dried leaves of *Acacia nilotica* and *Moringa oleifera* were finely powdered before extraction. For each sample, 50 g of leaf powder was combined with 500 mL of distilled water as the extraction solvent (1:10, w/v) and maintained on a shaker at ambient temperature (25 ± 2°C) for 24 hours with continuous agitation at 120 rpm. Following incubation, the mixture was centrifuged at 4000 rpm for 10 minutes, and the supernatant was carefully collected as the crude extract. The extracts were stored at 4°C until further use and subsequently diluted with distilled water to the required concentrations (0, 10, 15, and 20 ml L^{-1}) for foliar application. Spraying was conducted promptly after preparation to preserve the extracts' bioactive properties (Abubakar and Haque, 2020).

2.3. Measurement of parameters

2.3.1. Yield

All measurements conducted inside the greenhouse were performed from 06:00 a.m. to 09:00 a.m. To evaluate yield, three plants were selected and tagged as replicates in each treatment. Fruits were harvested from each plant in three successive pickings, and the weight of the harvested product at each picking was recorded. The final yield of each plant was calculated as the sum of the yields from the three pickings, and the total yield of the plants in each treatment was reported as the treatment yield.

2.3.2. Maximum quantum efficiency of photosystem II (Fv/Fm)

The maximum quantum efficiency of photosystem II (Fv/Fm) was determined following the protocol described by Maxwell and Johnson (2000). Leaf samples were dark-adapted for at least 20 minutes before being exposed to strong light pulses to record the minimal fluorescence (Fo) and maximal fluorescence (Fm). This method is widely recognized as a reliable and non-invasive approach for assessing photosynthetic performance due to its high accuracy and reproducibility, and it is considered a standard technique in plant physiology studies.

2.3.3. Photosynthetic index (PI)

The photosynthetic performance index (PI) was measured using a chlorophyll fluorometer (Hansatech LTD Pocket, UK) according to the manufacturer's guidelines.

2.3.4. SPAD

Leaf greenness was evaluated using a SPAD-502 handheld chlorophyll meter (Japan), with measurements taken on fully expanded leaves to ensure consistency.

2.3.5. Photosynthetic indices

CO_2 Assimilation Rate (A), transpiration rate (E), stomatal conductance (gs), and sub-stomatal CO_2 concentration (Ci) were measured using a photosynthesis meter (IRGA, LCi Ultra Compact, Herts ADC BioScientific Ltd, UK) (Porra, 2002).

2.4. Data analysis

Statistical analyses were performed using SAS software version 9.4. Duncan's multiple-range test was used to compare treatment means, with a significance threshold of $P \leq 0.05$. Additionally, OriginPro 2024 software was employed to compute correlation coefficients among the evaluated traits and to conduct principal component analysis (PCA).

3. Results

The results of the analysis of variance indicated that the applied treatments had a significant effect ($P \leq 0.01$) on all evaluated traits, including yield and photosynthetic indices (Table 1).

Table 1. Analysis of variance of the effects of *Moringa oleifera* and *Acacia nilotica* extract treatments on measured traits.

Source of Variation (S.O.V.)	df	SPAD (SPAD)	Quantum Eff. of PSII (Fv/Fm)	Photosynthetic Index (PI)	Intercellular CO2 Conc. (Ci)	Transpiration Rate (E)	Stomatal Conductance (gs)	CO2 Assimilation Rate (A)
Treatment	15	79.91**	0.001**	2.58**	5541.54**	6.19**	0.01**	16.42**
Block	2	43.91ns	0.00006ns	0.37ns	302.02ns	1.29ns	0.0007ns	0.58ns
Error	126	23.05	0.0004	0.58	988.01	0.64	0.0009	0.55
CV (%)	-	9.92	2.47	23.25	9.90	19.22	22.15	14.12

** indicates a significant difference at the 1% probability level.

3.1. Yield

The final yield reflects the combined effects of all physiological processes, including photosynthesis, transpiration, and vegetative growth. The highest yield was observed in the M (15 ml L^{-1}) + A (20 ml L^{-1}) and M (20 ml L^{-1}) treatments, with no significant difference between them (Figure 1). These results indicate that the simultaneous application of optimal extract concentrations or the use of *Moringa* at high concentrations can enhance plant metabolism, improve the translocation of photosynthetic assimilates to the fruit, and ultimately increase yield.

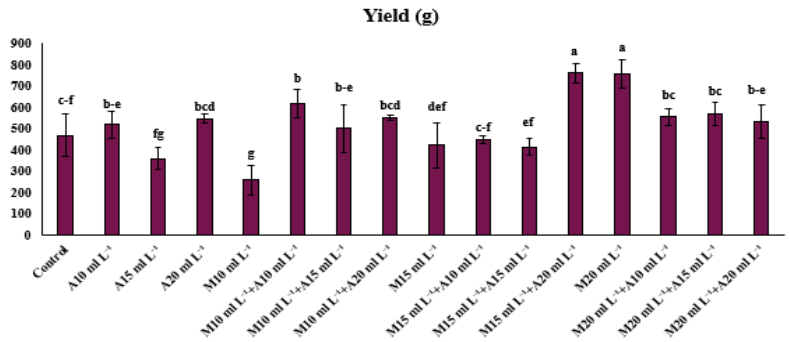


Figure 1. Effects of *Acacia* and *Moringa* extracts on tomato yield. Different letters indicate significant differences ($P \leq 0.05$).

3.2. Maximum quantum efficiency of photosystem II (Fv/Fm)

The Fv/Fm index reflects the quantum efficiency of photosystem II and overall photosynthetic health; its reduction typically indicates photochemical damage or light stress. In this study, the highest Fv/Fm value was recorded in the M (15 ml L^{-1}) +A (20 ml L^{-1}) treatment, suggesting improved PSII performance resulting from the combined application of a moderate *Moringa* extract (15 ml L^{-1}) and a high *Acacia* extract (20 ml L^{-1}), likely due to their antioxidant compounds and growth-promoting substances that protected chlorophyll and PSII (Figure 2). Conversely, the M (20 ml L^{-1})+A (20 ml L^{-1}) treatment showed the lowest Fv/Fm value, likely caused by excessive phenolic content, which led to inhibitory effects.

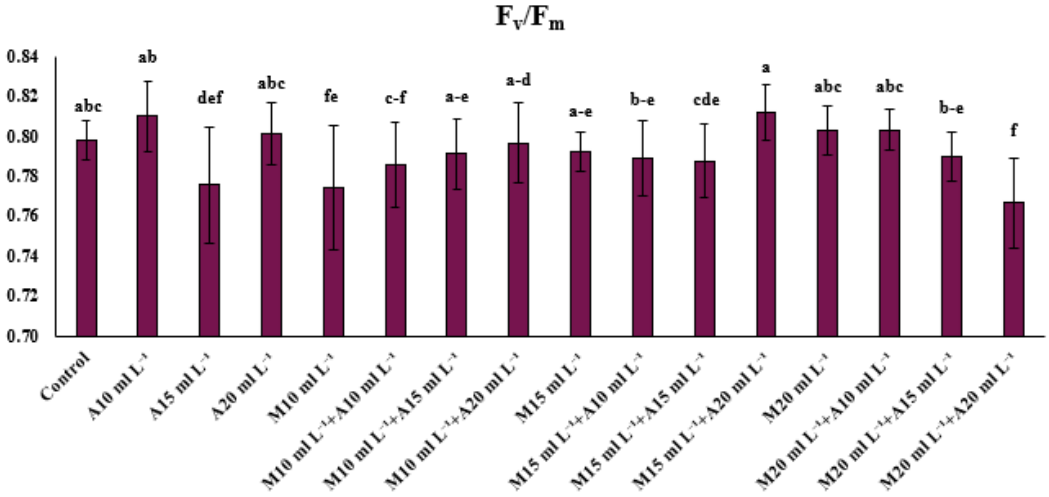


Figure 2. Effects of *Acacia* and *Moringa* extracts on Fv/Fm index in tomato plants. Different letters indicate significant differences (P ≤ 0.05).

3.3. Photosynthetic index (PI)

The PI index is a composite indicator that reflects energy flux in photosystem II, electron transport efficiency, and reaction center activity. The highest PI value was observed in the A (20 ml L^{-1}) treatment, indicating that high-concentration *Acacia* extract alone can improve photosynthetic performance, likely through its growth-stimulating effects and enhanced antioxidant activity. In contrast, the lowest PI value was observed in the M (20 ml L^{-1}) +A (20 ml L^{-1}) treatment, suggesting a negative impact of excessive concentrations of both extracts and the possible induction of physiological stress in the plant (Figure 3).

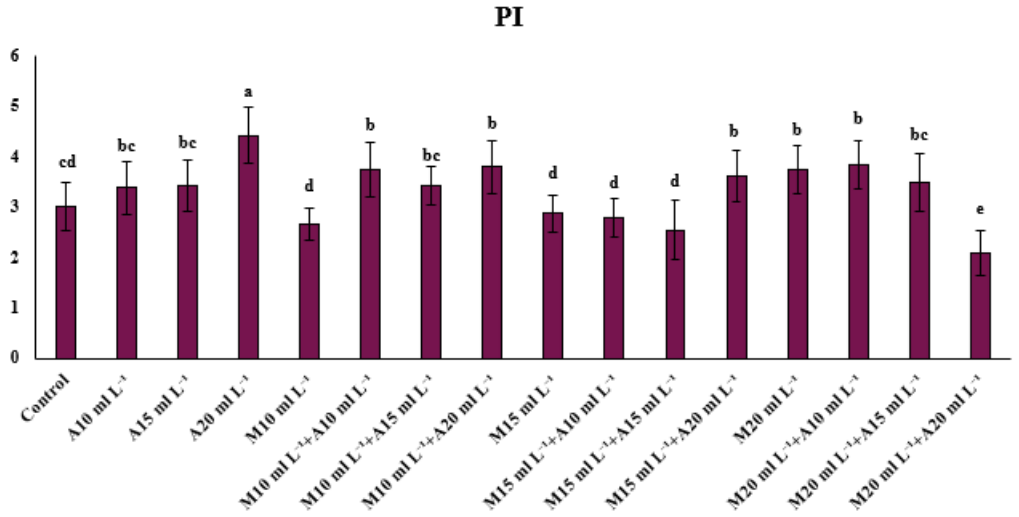


Figure 3. Effects of *Acacia* and *Moringa* extracts on PI index in tomato plant. Different letters indicate significant differences (P ≤ 0.05).

3.4. SPAD

The SPAD index indicates the relative chlorophyll content in leaves, directly linked to photosynthetic capacity. The highest SPAD value was recorded in the A (10 ml L^{-1}) treatment, reflecting the positive effect of low-dose *Acacia* on chlorophyll accumulation. Conversely, the lowest values were observed in M (20 ml L^{-1}) + A (10 ml L^{-1}) and M (20 ml L^{-1}) +A (15 ml L^{-1}), likely due to chlorophyll degradation caused by high *Moringa* concentrations (Figure 4). These results suggest that at elevated levels, *Moringa* phenolic compounds may inhibit pigment biosynthesis.

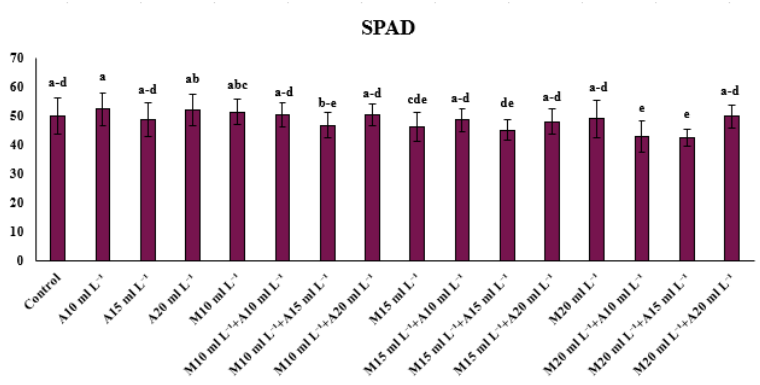


Figure 4. Effects of *Acacia* and *Moringa* extracts on SPAD in tomato plants. Different letters indicate significant differences (P ≤ 0.05).

3.5. CO_2 assimilation rate (A)

Photosynthetic rate reflects the plant's capacity for carbon fixation and biomass production. The highest rate was observed in the M (15 ml L^{-1}) + A (20 ml L^{-1}) treatment, with no significant difference from M (20 ml L^{-1}) (Figure 5). These findings indicate that combining a moderate *Moringa* concentration with a high *Acacia* concentration, or applying a high *Moringa* concentration alone, can maximize photosynthetic activity. This effect is likely associated with increased chlorophyll content, enhanced electron transport, and improved photosystem efficiency driven by growth-regulating compounds in the extracts.

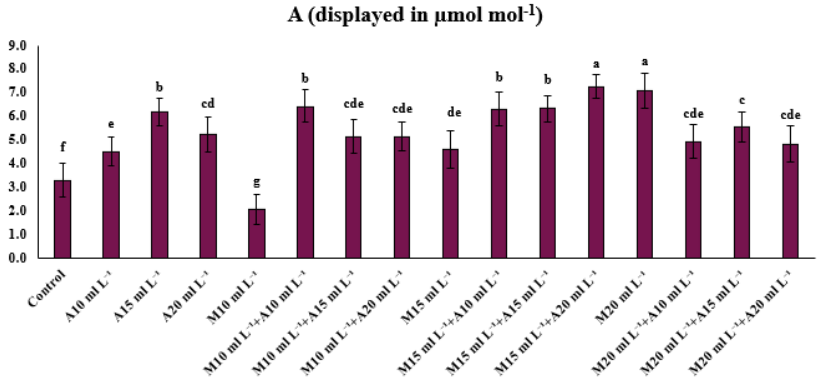


Figure 5. Effects of *Acacia* and *Moringa* extracts on CO2 assimilation rate (A) in tomato plant. Different letters indicate significant differences (P ≤ 0.05).

3.6. Transpiration rate (E)

Transpiration rate reflects stomatal activity and the plant's water balance. The highest rate occurred in the M (15 ml L^{-1} + A (20 ml L^{-1}) treatment, indicating open stomata and favorable water status under this combination, likely due to enhanced antioxidant enzyme activity, improved membrane stability, and increased water uptake. The lowest rate was recorded in M (10 ml L^{-1}), possibly resulting from restricted stomatal opening due to insufficient levels of bioactive compounds (Figure 6).

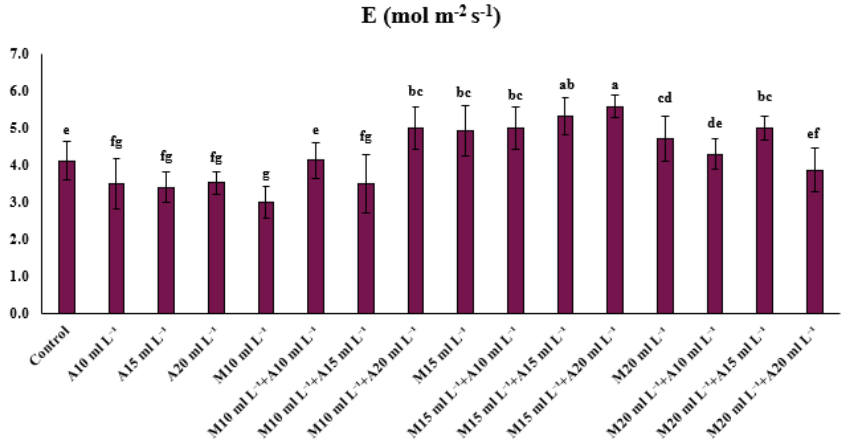


Figure 6. Effects of *Acacia* and *Moringa* extracts on transpiration rate (E) in tomato plant. Different letters indicate significant differences (P ≤ 0.05).

3.7. Stomatal conductance (gs)

Stomatal conductance (gs) is a key indicator of gas exchange that directly influences photosynthesis and transpiration. The highest Gs value was recorded in the M (10 ml L^{-1}) and A (10 ml L^{-1}) treatment, reflecting an optimal balance between stomatal aperture and water-use efficiency, likely due to the ability of moderate *Moringa* and *Acacia* concentrations to maintain osmotic balance and prevent stomatal closure. In contrast, treatments M (0 ml L^{-1}) + A (20 ml L^{-1}), M (10 ml L^{-1}), M (10 ml L^{-1}) +A (15 ml L^{-1}), M (20 ml L^{-1}) + A (10 ml L^{-1}), and M (20 ml L^{-1}) + A (20 ml L^{-1}) exhibited the lowest values, indicating reduced gas exchange under stress conditions or excessive extract concentrations (Figure 7).

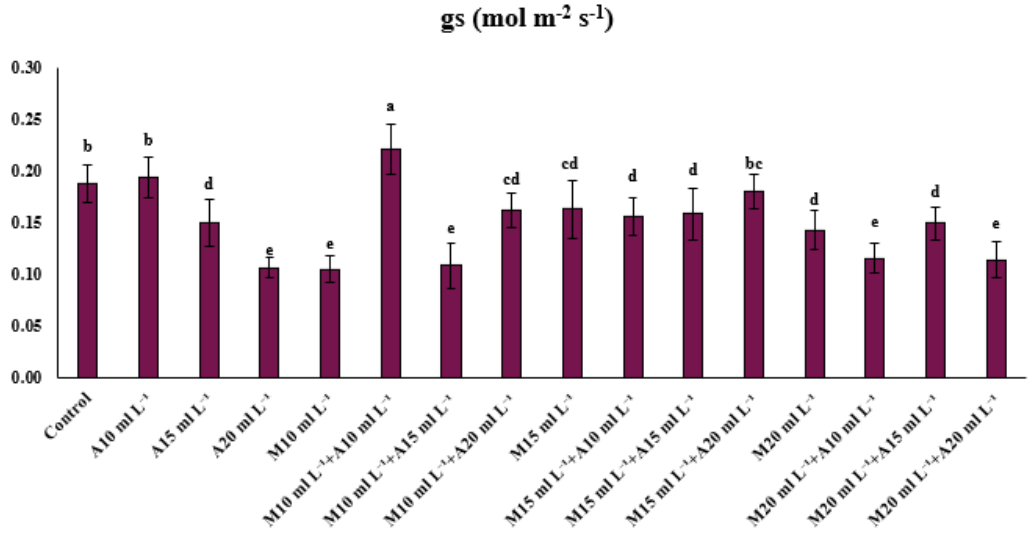


Figure 7. Effects of *Acacia* and *Moringa* extracts on stomatal conductance (gs) in tomato plant. Different letters indicate significant differences ($P \leq 0.05$).

3.8. Sub-stomatal CO_2 concentration (Ci)

Intercellular CO_2 concentration (Ci) reflects the balance between CO_2 uptake through stomata and its consumption during photosynthesis. Higher Ci values typically indicate greater stomatal openness and improved gas exchange. In this study, the highest Ci was observed in the M (10 ml L^{-1}) treatment, demonstrating enhanced CO_2 penetration into mesophyll cells. Conversely, the M (20 ml L^{-1}) treatment showed the lowest Ci value, possibly due to partial stomatal closure or restricted CO_2 uptake caused by the high *Moringa* concentration (Figure 8).

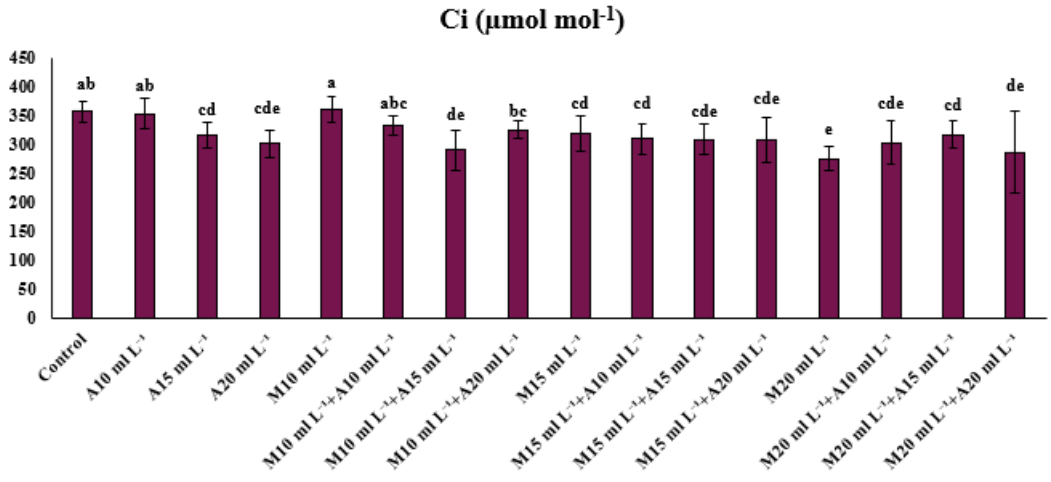


Figure 8. Effects of *Acacia* and *Moringa* extracts on sub-stomatal CO2 concentration (Ci) in tomato plant. Different letters indicate significant differences ($P \leq 0.05$).

3.9. Principal component analysis (PCA)

The PCA results indicated that PC1 and PC2 explained 40% and 22.5% of the total variance, respectively. Photosynthetic indices FV/FM and PI, along with Yield, were positively associated along PC1, while photosynthetic rate (A) and transpiration (E) were moderately correlated but somewhat distant from Yield. Gas exchange parameters (Ci and gs) were oriented differently, showing negative or distinct correlations with Yield. These results highlight the importance of photosynthetic traits and leaf health in determining plant performance (Figure 9).

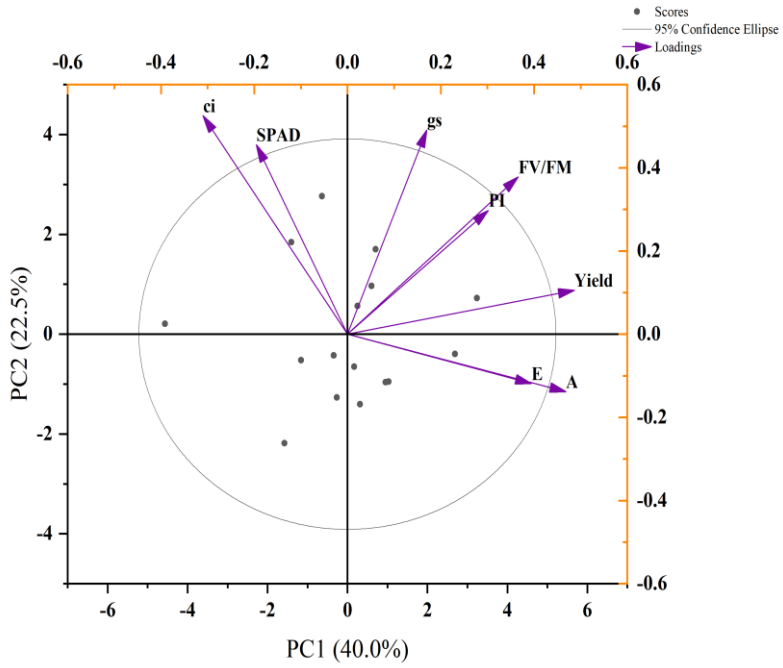


Figure 9. Principal component analysis (PCA) of *Acacia* and *Moringa* extracts on yield and photosynthetic parameters in tomato plant.

3.10. Correlation

The correlation matrix showed that leaf health and photosynthetic indices such as SPAD, FV/FM, and PI were positively correlated with each other and with Yield (e.g., FV/FM vs. Yield: r = 0.60). Photosynthetic rate (A) and transpiration (E) also displayed moderate positive correlations (r = 0.58), whereas intercellular CO_2 concentration (Ci) was negatively correlated with Yield (r = -0.48). These findings emphasize that photosynthetic traits have the most positive impact on plant performance, while some traits like Ci may exert a negative or different effect (Figure 10).



Figure 10. Pearson correlation analysis of *Acacia* and *Moringa* extracts with yield and photosynthetic parameters in tomato plant.

4. Discussion

This study showed that applying a combination of *Moringa* leaf extract and *Acacia* at moderate to high levels notably improved tomato growth and productivity. The observed enhancement is likely linked to the abundant bioactive substances in *Moringa*, such as zeatin and other cytokinins, which can promote cell division, photosynthetic efficiency, and the movement of photosynthates to reproductive parts (Rady et al., 2013). Moreover, *Acacia* extract, containing polysaccharides and phenolic compounds, may provide additional growth-stimulating and antioxidant effects, amplifying the benefits of *Moringa* when used together. Consistent with these results, previous research has indicated that foliar

application of *Moringa* extract boosts tomato performance (Ngcobo et al., 2024). This improvement is thought to result from enhanced vegetative development, stronger root systems, and increased photosynthetic activity (Mashamaite et al., 2022).

The Fv/Fm ratio, which reflects the efficiency of photosystem II and the integrity of photosynthetic structures, was significantly enhanced by the application of biostimulants. This increase is likely due to the structural protection of PSII reaction centers and the prevention of photooxidative damage. The effect may be associated with the presence of natural antioxidants and phenolic compounds in *Moringa* and *Acacia* extracts, which help protect the D1 protein and thylakoid membranes (Abd El-Mageed et al., 2017). Such a mechanism typically maintains high actual quantum yield under optimal growth conditions. Similarly, Giannakoula et al. (2024) reported that the application of natural growth stimulants improves the preservation of photosystem II efficiency and enhances photosynthetic performance in *Aronia melanocarpa*. Additionally, Mollo et al. (2025) emphasized that biostimulant treatments increase Fv/Fm and promote PSII health in plants, indicating an overall improvement in photosynthetic efficiency.

The photosynthetic performance index (PI), a comprehensive indicator of electron transport efficiency, was increased in plants treated with biostimulants. This enhancement is likely due to improved electron transport capacity and more efficient use of light energy in photochemical reactions. The effect may result from the supply of essential elements such as Mg and K, along with bioactive compounds in the extracts, which help stabilize membrane proteins and PSII reaction centers (Basra and Lovatt, 2016). Higher PI under normal conditions generally reflects optimal light energy utilization and effective production of photosynthetic compounds. Zuo et al. (2025) demonstrated that the application of calcium compounds along with biostimulants enhances PI and overall photosynthetic performance in rice under salt stress. Similarly, Giannakoula et al. (2024) reported that biostimulants contribute to better protection of the electron transport chain and an increase in PI, particularly under environmental stress conditions.

The higher SPAD values observed in the M0A10 treatment can be attributed to the synergistic effect of *Moringa* and *Acacia* in preserving chlorophyll and enhancing chlorophyll synthase activity (Figure 4). *Moringa* extract, by supplying essential micronutrients such as Mg and Fe along with antioxidant compounds, helps prevent chlorophyll degradation (Babarabie et al., 2025), while *Acacia*, through complementary growth-promoting effects, increases pigment stability. In contrast, the reduced SPAD values in M20A10 and M20A15 treatments are likely due to the negative impact of high *Moringa* concentrations on mineral balance and the induction of osmotic stress, ultimately decreasing chlorophyll synthesis and stability (Babarabie and Zarei, 2024).

Changes in transpiration rate (E), an important parameter reflecting the balance between CO_2 uptake and water loss, are highly significant. The observed increase in E is likely due to more efficient stomatal opening and closing and improved plant water status. These conditions may be facilitated by physiological regulators such as cytokinins and enhanced potassium nutrition, which play a key role in stomatal activity (Abd El-Mageed et al., 2017). Higher E under these circumstances can help dissipate excess heat and improve leaf cooling. Research has shown that biostimulants enhance transpiration rates and better regulate stomatal movements, ensuring adequate CO_2 supply for photosynthesis in radish plants (Raza et al., 2022). These findings are consistent with Cristiano et al. (2018), who reported positive effects of plant-animal-based stimulants on transpiration and gas exchange in Snapdragon.

Stomatal conductance (gs) plays a crucial role in regulating gas exchange and photosynthetic processes. The rise in gs likely reflects enhanced guard cell activity and greater stomatal aperture. This response may result from the modulation of hormonal balance (ABA and cytokinins) by the bioactive compounds present in the extracts. Such regulation typically promotes increased CO_2 assimilation, ultimately improving net photosynthesis (Mashamaite et al., 2022). It has been reported that the application of biostimulants leads to a marked increase in gs, facilitating higher CO_2 uptake and consequently improving photosynthetic efficiency (Shahrajabian et al., 2021). Similarly, increased gs in response to stimulants has been associated with overall improvements in plant phenotypic status and photosynthetic performance (Cristiano et al., 2018).

Intercellular CO_2 concentration (Ci) reflects the plant's gas-exchange capacity and the amount of CO_2 available for photosynthesis. Higher Ci values are likely associated with wider stomatal opening and reduced resistance along the CO_2 diffusion pathway. This response may result from improved leaf water status and osmotic regulation influenced by growth-promoting hormones present in the extracts (Mashamaite et al., 2022). More efficient Rubisco activation may also contribute to this increase. Silva et al. (2025) reported that plant-based stimulatory compounds enhanced Ci and improved gas-exchange performance in bell pepper under salinity stress. Such elevation in Ci may indicate better CO_2 uptake and more effective utilization, aligning with the findings of Zulfiqar et al. (2020), who demonstrated that natural plant extracts can significantly enhance gas exchange and photosynthesis.

The positive correlations of SPAD, Fv/Fm, and PI with yield indicate that chlorophyll content and photosystem II (PSII) integrity were key determinants of plant performance in this study. Chlorophyll fluorescence parameters such as Fv/Fm and PI are widely recognized as sensitive indicators of photosynthetic efficiency and plant health, and their association with plant performance has been confirmed across species and stress conditions (Faseela et al., 2020). The positive link between SPAD and yield is also consistent with the capacity of foliar biostimulants, particularly *Moringa* leaf extract, to enhance chlorophyll accumulation, photosynthetic activity, and final crop productivity (Yuniati et al., 2022). The

importance of such physiological indicators in yield formation has likewise been emphasized for other crops (Szulc et al., 2021).

The negative correlation between intercellular CO_2 concentration (Ci) and yield ($r = -0.48$) suggests that high-yielding plants utilized internal CO_2 more efficiently for carbon assimilation, leaving a lower residual Ci under active photosynthesis. This pattern reflects strong carboxylation capacity and is typical of plants with improved photosynthetic performance (Yan et al., 2024). Furthermore, the moderate positive correlation between photosynthetic rate (A) and transpiration (E) indicates coordinated stomatal regulation that balances carbon gain with water loss, a feature commonly improved by biostimulant application and associated with enhanced growth and yield (Bhupenchandra et al., 2022). Overall, the PCA and correlation analyses show that the combined improvement in chlorophyll status, PSII efficiency, and gas-exchange regulation contributed to the higher yield recorded in plants treated with *Moringa* and *Acacia* leaf extracts.

5. Conclusion

The results of this study showed that the plant extracts of *Moringa oleifera* and *Acacia nilotica*, particularly when applied in combination, have considerable potential to improve growth, photosynthetic performance, and fruit yield of tomato under greenhouse conditions. Overall, the findings showed that the use of these plant-derived compounds can contribute to increased productivity through improving the physiological and photosynthetic status of the plant and can be considered a promising approach in tomato production management. From a practical point of view, these results indicate that plant extracts can be introduced as natural supplements in greenhouse production systems, particularly under conditions where reducing dependence on chemical inputs and moving toward sustainable agriculture are important. However, before broad practical recommendations can be made, the effectiveness of these compounds should be examined more precisely under different environmental conditions, cultivation systems, and alongside conventional plant nutrition programs. Future research should also focus on identifying the active compounds present in these extracts, further clarifying their physiological and biochemical mechanisms of action, and evaluating the stability of plant responses in other horticultural crops and under field cultivation conditions. Such studies can provide the basis for a more targeted use of plant-based biostimulants in sustainable horticultural production.

Authors' contributions

M. B. conceptualized the research and oversaw the greenhouse trials. S. A. contributed to laboratory work and equipment, as well as conducted data analysis and interpretation. A. M. D. Advice on how to plant and maintain plants. A. R. and A. M. B. are doing greenhouse work. A. D. In writing the article. All authors critically reviewed the final manuscript and approved its publication, affirming their agreement with the study's content and conclusions.

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