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OPTIMIZING TOMATO GROWTH AND YIELD THROUGH THE INTEGRATED APPLICATION OF *AZOLLA PINNATA* AND SYNTHETIC FERTILIZERS

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ABSTRACT

Increased dependence on chemical fertilizers has raised concerns over reduced soil health and increased environmental degradation. Options that reduce the dependence on chemical fertilizers without affecting the quality and quantity of the yield have gained importance. Azolla pinnata, a nitrogen fixing cyanobacteria, proves to be a viable alternative in that concern. This study was set out to examine how well *A.pinnata* works as a sustainable alternative, both by itself and in combination with synthetic fertilizers, to improve tomato (*Solanum lycopersicum*) plant growth, nutrient uptake, and yield while lowering the dependence on chemical fertilizers. A study was conducted to examine the effect of the combined application of *Azolla pinnata* and chemical fertilizers from March 2024 to Jun 2024 at JSS AHER, Mysore, Karnataka. This study examined the effects of eight treatments on tomato plants, which included a control group with no fertilizers, 100% synthetic fertilizers, and various combinations of *A. pinnata* and synthetic fertilizers. Plant growth parameters, along with fruit number and fruit weight, were analyzed to evaluate the effectiveness of each treatment. The best results were obtained with T_6 in increased plant height of 64.02 cm, a leaf area index of 1.52, an average of 33.01 fruits per plant, and a fruit weight of 50.16 g when 50% NPK and 50% *A. pinnata* were applied together. he results indicate that partial replacement of synthetic fertilizer with Dry *A. pinnata* biomass produced comparable responses for selected growth and yield components under the conditions of the present experiment. The results highlight *A. pinnata*'s potential for sustainable farming and lessen the negative effects of chemical fertilizers.

Keywords: Biofertilizer, Cyanobacteria, Environmental sustainability, Nitrogen fixation, Sustainable agriculture, Synthetic fertilizer

INTRODUCTION

Even though the Earth's atmosphere is changing continuously, the rate of change has accelerated significantly in the last two centuries **(DeRigne & Benevolenza, 2019)**. Climate-related disruptions in food systems have a direct effect on food security, which is a major determinant of human health **(Schnitter & Berry, 2019)**. Strong yield losses, particularly for maize and wheat crops, are anticipated in lower latitudes at higher warming levels **(Ray *et al.*, 2019; Okolie *et al.*, 2022)**. Some estimates state that in order to meet the expected food demand brought on by population increase and the continuous move to richer diets, global agricultural output will need to at least quadruple by 2050 **(Beltran-Peña *et al.*, 2020; Ray *et al.*, 2019)**.

The industrial and green revolutions considerably increased crop yields per unit area to fulfill the food demands of an expanding population, but this success was accompanied by a huge increase in the use of chemical fertilizers **(Kumar *et al.*, 2019; John & Babu, 2021)**. While socioeconomic growth can aid adaptation, the continued pressures of climate change will continue to necessitate adaptive solutions **(Schleussner *et al.*, 2021)**. The residual fertilizers in the soil either drain into nearby rivers or produce insoluble inorganic salts, which is seen to be a serious danger to soil biodiversity worldwide **(Bai *et al.*, 2020)**.

Solanum lycopersicum, commonly known as tomato, is one of the most important vegetables grown all over the world. Tomato is a rich source of essential nutrients such as vitamins A, C, and antioxidants like lycopene, which play a vital role in improving human health **(Gerszberg *et al.*, 2015)**. Tomato cultivation in India is considered an important economic activity owing to its huge demand and short growth duration, resulting in a good economic return for farmers. Nevertheless, tomato growth entirely relies on nutrient availability, particularly NPK nutrients like nitrogen, phosphorus, and potassium **(Tiwari *et al.*, 2022)**.

Azolla is an aquatic fern that fixes Nitrogen(N) from the atmosphere and releases some of the fixed nitrogen to the rice plants. *A. pinnata* and the N-fixing cyanobacteria work together to produce a high nitrogen content of 3–5%. *A. pinnata* can be composted or added as fresh biomass as an organic fertilizer to rice fields **(Setiawati *et al.*, 2018; Ting *et al.*, 2022)**.

MATERIALS AND METHODS

This study evaluated the influence that applying Azolla pinnata in conjunction with chemical fertilizers would have on growing tomato plants (*Solanum lycopersicum* L.) and the overall yield produced by those tomato plants. Pot Experiment was carried out from March to June 2024 in the normal field conditions of JSS Academy of Higher Education & Research (JSS AHER), Mysuru, Karnataka, India. The tomato seedlings were transplanted into the grow bags that were prepared and kept for growth until maturity and harvesting. Growth of the plants was observed at regular intervals during the experiment. Although the observations were done at regular intervals, only those observations which were made at the end of the experimental period have been discussed here. Regular activities suitable for growing tomatoes under the existing environment in the field where the experiment was being conducted were undertaken throughout the experiment, which included irrigating the tomatoes regularly and undertaking general plant management activities. Specific pest management activity using any pesticides was not undertaken in the experiment, and the presence of pests and diseases in the plants was monitored regularly.

Azolla biomass preparation and analysis

Fresh azolla (*A. pinnata*) was taken from the prepared pond at JSS AHER in Mysuru. The harvest was washed with distilled water to remove any extraneous particles. The plant material was then dried in a hot air oven at 50 degrees Celsius until its weight stayed constant. The dried material was crushed and sieved through a 2mm sieve to ensure uniform particle size. A nutrient content analysis was then performed on the sample, as indicated in Table I. The material was mixed directly with the soil during the pre-treatment process.

Table 1 Compositional analysis of Dried Azolla biomass

Traits	pH	Organic Carbon	N%	P%	K%	C/N Ratio	Zn (ppm)	Fe (ppm)
Values	7.15	19.2%	3.1%	0.96%	1.5%	11.21	68.15	570

Plant Material and Growing Conditions

Tomato (*Solanum lycopersicum* L.) seeds of the variety Arka Vikas, developed by the ICAR-Indian Institute of Horticultural Research (ICAR-IIHR), Bengaluru, were used for the experiment. Arka Vikas is an open-pollinated tomato variety suitable for both rainfed and irrigated conditions. The experiment was conducted in Mysuru, Karnataka, India, under the prevailing climatic conditions of the study area. Tomato seeds were initially sown and maintained for 60 days after sowing, after which the plants were transferred to the experimental grow bags. Irrigation was provided when required based on the moisture condition of the growing medium, avoiding excessive watering. The plants were maintained under the prevailing environmental conditions of the study area throughout the experimental period.

Experimental Treatments and Experimental Design

The pot trial was performed using a Randomized Complete Block Design (RCBD) with eight nutrient treatments and three replications, resulting in a total of 24 experimental units. In each replication, all eight treatments were included, and the positions of the treatments were randomized to minimize the effects of spatial variation under field conditions. Each experimental unit consisted of one black plastic grow bag (10 × 12 inches) containing 2 kg of soil and one tomato plant. The treatments consisted of different proportions of the recommended NPK dose and dried *Azolla pinnata* biomass (DAB). The treatment structure was as follows: T1 = Control (0% NPK + 0% DAB); T2 = 100% NPK; T3 = 70% NPK; T4 = 40% NPK; T5 = 100% DAB; T6 = 50% NPK + 50% DAB; T7 = 70% NPK + 30% DAB; and T8 = 40% NPK + 60% DAB. The full DAB application rate was set at 3 t ha^{-1} for the 100% DAB treatment. The DAB application rate was converted to the pot application rate based on a soil depth of 15 cm and a soil bulk density of 1.3 g cm^{-3}. Accordingly, a soil mass of 1,950,000 kg ha^{-1} was considered, corresponding to 1.538 g DAB kg^{-1} soil; therefore, 3.08 g DAB was applied to each grow bag containing 2 kg soil for the 100% DAB treatment. Based on this application rate, 1.54, 0.92, and 1.85 g DAB were applied per pot for the 50%, 30%, and 60% DAB treatments, respectively. The nutrient contribution from DAB was calculated based on its chemical composition, which contained 3.1% N, 0.96% P, and 1.5% K. The percentages assigned to DAB and NPK represented proportions of their respective predetermined full application rates and were not nutrient-equivalent treatments.

Table 2 Soil chemical parameters

Parameter (unit)	Value	Interpretation
Moisture content (%)	1.33	-
pH	7.21	Alkaline
Electrical conductivity (EC-dsm^{-1})	0.18	Harmless
Available Nitrogen (N) kg/acre	137	Medium
Phosphorus (P_2O_5) kg/acre	13	Medium
Potassium (K) kg/acre	61	Medium
Organic Carbon (OC) %	0.53	Medium

Table 3 Treatments used in the experiment

Treatment	Treatment description
T1	Control (0% NPK + 0% DAB)
T2	100% NPK
T3	70% NPK
T4	40% NPK
T5	100% DAB
T6	50% NPK + 50% DAB
T7	70% NPK + 30% DAB
T8	40% NPK + 60% DAB

Note: The recommended full NPK dose was 100 kg ha^{-1} N, 50 kg ha^{-1} P_2O_5, and 45 kg ha^{-1} K_2O. The DAB percentages represent proportions of the full DAB application rate of 3 t ha^{-1}. NPK and DAB treatments were not nutrient-equivalent.

Plant growth

At the blooming stage, tomato plants in each plot were selected at random, and their leaf area index (LAI), dry matter production (DMP), and total chlorophyll content were measured. Total chlorophyll content was measured at 645 and 663 nm using a UV spectrophotometer. DMP weight (g plant^{-1}) was calculated using the methods outlined by **Heuvelink (1995)** and **Nagata *et al.* (2001)**. To calculate the leaf area index (LAI), the ratio of the plants' leaf areas (cm^2) to their ground area (cm^2) was calculated.

Yield Components

To measure the height of the tomato plants (cm) and the number of fruits on each tomato plant, selected plants were randomly pulled from the middle of the pot at the point of maturity. The mature fruit was harvested at set intervals to get a total count of the number of mature fruits by tree. Randomly selected representative fruits are weighed (g) using an electronic balance and measured for length and diameter (cm) with a vernier caliper from representative separate samples. These measurements were used to assess the effects of the treatments on tomato growth and selected yield components, including fruit number and average fruit weight.

Nutrient Uptake

At the end of the experiment, one representative plant showing the best overall performance was selected from each treatment for nutrient-uptake analysis. The selected plant material, including the plant and fruit components, was oven dried at 70 °C until a constant weight was obtained, ground into a fine powder, and subjected to acid digestion. Total nitrogen (N) was determined by the micro-Kjeldahl method following digestion with concentrated sulphuric acid **(Murthy *et al.*, 2024)**. Phosphorus (P) was determined colorimetrically by the ascorbic acid method using a UV–Visible spectrophotometer (Aligent carry 60) **(Wieczorek *et al.*, 2022)**. Potassium (K) was determined by flame photometry using a potassium-specific filter (Asch *et al.*, 2024.); the potassium analysis was performed by an outsourced analytical laboratory. Nutrient concentrations obtained from the respective analytical determinations were used together with the corresponding plant dry matter to calculate nutrient uptake, expressed as kg ha^{-1}. Because one representative plant was selected from each treatment for nutrient analysis, the resulting nutrient-uptake values are presented as descriptive measurements and were not subjected to statistical comparison or variability estimation.

Nutrient uptake was expressed on a hectare basis by scaling the nutrient content measured in the 2 kg soil-filled pot to the equivalent soil mass of 1,950,000 kg ha^{-1}. The equivalent soil mass was estimated assuming a soil depth of 15 cm and a soil bulk density of 1.3 g cm^{-3}. Nutrient uptake was calculated using the following equation:

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient concentration (\%)} \times \text{Plant dry matter (kg)}}{100} \times \frac{Equivalent\ soil\ mass}{2}$$

where nutrient concentration represents the measured N, P or K concentration in the dried plant material, plant dry matter represents the corresponding dry biomass obtained from each 2 kg soil-filled pot, 2 kg is the soil mass per experimental unit, and 1,950,000 kg ha^{-1} represents the estimated soil mass within a 15 cm soil depth at a bulk density of 1.3 g cm^{-3}. The conversion assumes uniform soil depth and bulk density and was used to express pot-scale nutrient uptake as kg ha^{-1}.

Statistical Analysis

Data was analyzed using the Data Analysis ToolPak in Microsoft Excel 2021. The experiment followed a Randomized Complete Block Design (RCBD) with eight treatments and three replications, with each grow bag considered an experimental unit. For each parameter, ANOVA: Two-Factor Without Replication was used to evaluate treatment effects while accounting for replication/block effects. The treatment, replication, error, and total degrees of freedom were 7, 2, 14, and 23, respectively. The treatment F-value was calculated as $F = MS_{\text{treatment}}/MS_{\text{error}}$, and statistical significance was assessed at $p < 0.05$. Following significant ANOVA results, treatment means were compared using the Least Significant Difference (LSD) test at the 5% level, calculated as $LSD = t_{0.025,14}\sqrt{2MS_e/3}$, where MS_e is the residual mean square and three is the number of replications. Means differing by more than the calculated LSD were considered significantly different and assigned different grouping letters. Results are presented as mean ± SD (n = 3). The analysis assumed independent experimental units, approximately normally distributed residuals, and homogeneous variance; however, no formal residual normality or homogeneity tests were performed.

RESULTS AND DISCUSSION

Effect of Azolla Biomass, Synthetic Fertilizers and Their Combinations on Plant Growth

Table 4 Effect of Azolla Biomass, Synthetic Fertilizers and Their Combinations on Chlorophyll content, Leaf Area Index and Dry matter Production

Treatment	Chlorophyll content	Leaf Area Index (LAI)	Dry Matter Production (DMP)
T1	10.04 ± 0.67^{c}	0.79 ± 0.06^{c}	9.42 ± 0.22^{a}
T2	12.60 ± 0.70^{b}	1.26 ± 0.08^{b}	11.42 ± 0.23^{c}
T3	11.02 ± 0.68^{c}	1.07 ± 0.06^{e}	10.50 ± 0.22^{d}
T4	17.05 ± 0.75^{a}	0.92 ± 0.07^{d}	9.82 ± 0.21^{ab}
T5	18.06 ± 0.79^{a}	0.91 ± 0.06^{cd}	9.86 ± 0.20^{b}
T6	13.60 ± 0.68^{b}	1.52 ± 0.08^{a}	10.76 ± 0.24^{d}
T7	12.80 ± 0.60^{b}	1.61 ± 0.08^{a}	11.24 ± 0.23^{c}
T8	13.06 ± 0.63^{b}	1.36 ± 0.06^{b}	10.51 ± 0.21^{d}
SEm ±	**0.372**	**0.04**	**0.135**

LSD (5%)	**1.128**	**0.122**	**0.409**
CV (%)	**4.76**	**5.91**	**2.24**
F-value	**54.763**	**56.803**	**27.314**
p-value	**<0.001**	**<0.001**	**<0.001**

Note: Values are mean ± SD (n = 3). Means followed by different superscript letters within a column differ significantly according to LSD test at the 5% probability level, whereas means sharing a common letter are not significantly different.

According to the results, the treatments had a significant effect on all three parameters of plant growth, including chlorophyll content, leaf area index (LAI), and dry matter production (DMP) ($p < 0.001$). The chlorophyll content between the treatments differed significantly ($F_{7,14}$=54.763, $p < 0.001$). As reported in the results, T5 ranked first in terms of chlorophyll content (18.06) followed by T4 (17.05). These two treatments, therefore, were comparable, while T2 (12.60), T6 (13.60), T7 (12.80) and T8 (13.06) treatments were comparable to one another. The higher values of chlorophyll content in T5 indicate the success of this treatment in improving chlorophyll content compared to control and the other treatments.

The treatments exercised influence on leaf area development ($F_{7,14}$ = 56.803, $p < 0.001$). T7 had the maximum Leaf Area Index (LAI) of 1.61, which is statistically similar to T6 (1.52) while T8 (1.36) and T2 (1.26) formed the next higher statistical group. Treatments T3 (1.07), T4 (0.92), T5 (0.91), and T1 (0.79) also showed lower values of LAI with significant differences in the statistical grouping among the treatments. The effect of treatments also appeared significant in terms of dry matter production (DMP) ($F_{7,14}$ = 27.314, $p < 0.001$). The highest DMP was produced by T2 (11.42) followed by T7 (11.24) while T1 produced the lowest DMP (9.42). T2 and T7 were statistically similar while T1 and T4 indicated overlapping statistical grouping. Thus, the treatments showed various effects on some aspects of plants growth with T5 for chlorophyll content, T7 for leaf area index, and T2 for DMP.

Table 5 Effect of Azolla biomass, Synthetic Fertilizers, and Their Combinations on Plant height, No of Fruits per plant, and Average weight of fruits.

Treatment	Plant height (cm)	Number of fruits plant^{-1}	Average fruit weight (g)
T1	60.38 ± 0.31^{c}	10.66 ± 1.38^{c}	25.60 ± 1.99^{d}
T2	63.25 ± 0.31^{ab}	28.96 ± 1.62^{b}	42.11 ± 1.95^{c}
T3	62.26 ± 0.29^{bc}	26.07 ± 1.36^{c}	38.12 ± 1.75^{d}
T4	61.41 ± 0.32^{c}	26.91 ± 1.43^{bc}	36.50 ± 1.95^{d}
T5	62.06 ± 0.32^{bc}	28.02 ± 1.43^{bc}	56.25 ± 1.95^{a}
T6	64.02 ± 0.30^{a}	33.01 ± 1.55^{a}	50.16 ± 1.90^{b}
T7	63.51 ± 0.33^{a}	26.53 ± 1.38^{c}	49.12 ± 1.95^{b}
T8	61.92 ± 0.31^{bc}	25.56 ± 1.43^{c}	42.26 ± 1.80^{c}
SEm ±	**0.186**	**0.865**	**1.175**
LSD (5%)	**0.563**	**2.625**	**3.563**
CV (%)	**0.52**	**5.83**	**4.79**
F-value	**41.424**	**56.844**	**65.493**
p-value	**<0.001**	**<0.001**	**<0.001**

Note: Values are mean ± SD (n = 3). Means followed by different superscript letters within a column differ significantly according to the LSD test at the 5% probability level. Means sharing at least one common letter are not significantly different. SEm ± = standard error of mean; LSD = least significant difference; CV = coefficient of variation.

From the statistical analysis, it is evident that the treatments had a significant effect on the measured growth and yield-component parameters, namely plant height, number of fruits per plant, and average fruit weight ($p < 0.001$). Plant height differed significantly among treatments ($F_{7,14}$ = 41.424, $p < 0.001$). T6 recorded the highest plant height (64.02 cm), followed by T7 (63.51 cm) and T2 (63.25 cm), whereas T1 recorded the lowest value (60.38 cm). The overall comparison showed that T6 and T7 were statistically similar, while T1 recorded a lower plant height than several of the other treatments. These results indicate that the application of T6 and T7 supported greater vegetative growth under the conditions of the experiment.

The number of fruits produced per plant was also significantly affected by the treatments ($F_{7,14}$ = 56.844, $p < 0.001$). T6 recorded the highest number of fruits (33.01 fruits plant^{-1}), followed by T2 (28.96 fruits plant^{-1}) and T5 (28.02 fruits plant^{-1}), whereas T1 recorded the lowest number of fruits (10.66 fruits plant^{-1}). Average fruit weight showed a significant treatment effect ($F_{7,14}$ = 65.493, $p < 0.001$). T5 recorded the highest average fruit weight (56.25 g), followed by T6 (50.16 g) and T7 (49.12 g), whereas T1 recorded the lowest value (25.60 g). T5 was statistically superior in terms oFf average fruit weight, while T6 and T7 recorded statistically similar intermediate values. Overall, the treatments produced different responses across the measured growth and yield components. T6 recorded the highest numerical plant height and fruit number, whereas T5 recorded the highest numerical average fruit weight. These findings demonstrate treatment effects on selected yield components; however, because cumulative fruit yield per plant or yield per unit area was not determined, the results cannot be used to conclude that any treatment increased or maintained total tomato yield.

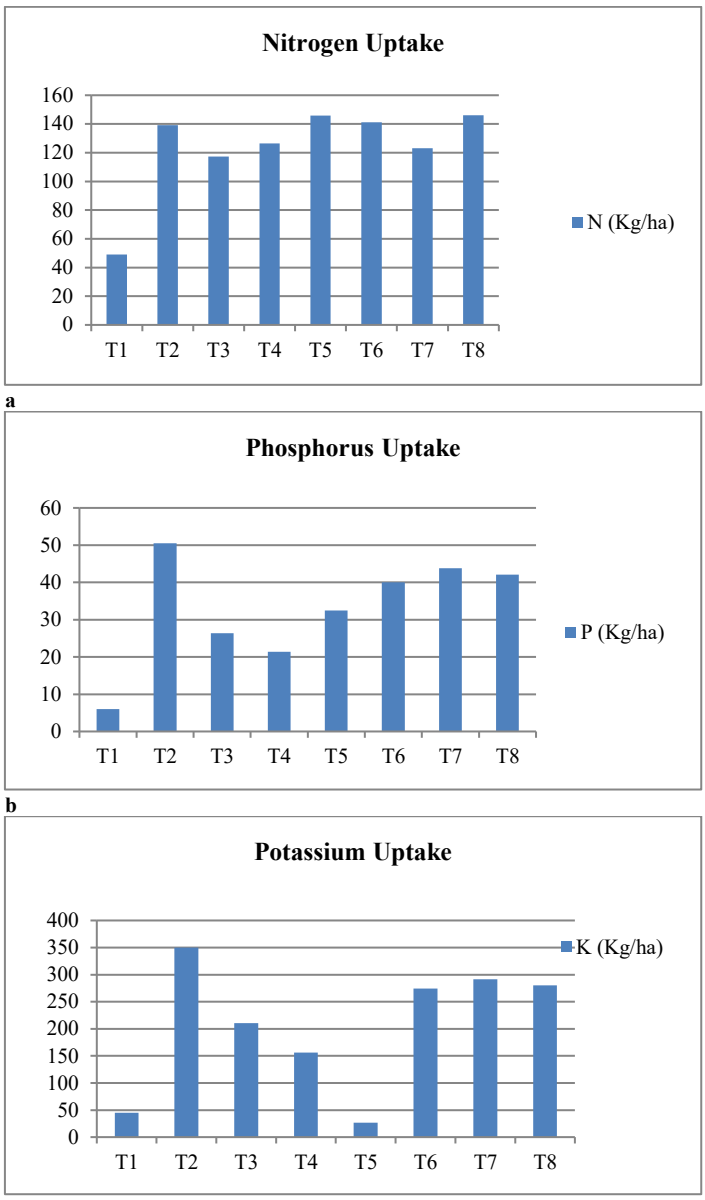

Figure 1 Nutrient uptake by tomato plants after the experiment: (a) nitrogen, (b) phosphorus, and (c) potassium.

The application of Azolla biomass (DAB) and synthetic fertilizers, both individually and in combination, resulted in significant variations in the growth and yield-component parameters of tomato. The integration of DAB with synthetic fertilizers generally resulted in improved plant performance compared with the control, although the response varied depending on the parameter considered. The results indicate that the combined application of organic and synthetic nutrient sources can influence nutrient availability and plant growth.

The highest nitrogen uptake of 139.2 kg/ha was found in T2 (100% NPK), indicating the rapid availability of nitrogen supplied by synthetic fertilizers. However, nitrogen uptake in T8 (40% NPK + 60% Azolla) exceeded that in T2 at 146 kg/ha, despite having lower amounts of synthetic fertilizer supplied. The consistent availability of nitrogen through the decomposition of the DAB may have contributed to nitrogen availability during crop development; however, nitrogen losses through leaching or volatilization were not measured in the present study. Similar findings were reported by **Yang *et al.* (2021)**, where the addition of Azolla to synthetic fertilizers improved nitrogen availability and NUE in rice production systems.

T5, with all-Azolla treatment, also demonstrated high nitrogen performance with 145.8 kg/ha of nitrogen. In comparison to synthetic fertilizers, nitrogen supplied through DAB may become available progressively through decomposition and mineralization; however, nutrient runoff and environmental contamination were not measured in the present study **(Arora *et al.*, 2023)**.

The T2 resulted in the highest phosphorus levels (50.5 kg/ha) due to the immediate availability of phosphorus in the fertilizer. Even though T8 (42.1 kg/ha) and T6 (40 kg/ha) used lower amounts of synthetic fertilizer, they were still competitive in terms of phosphorus levels. Azolla-associated changes in soil microbial activity have been suggested to promote the mobilization of previously unavailable soil

phosphorus **(Mahm *et al.* 2020)**; however, microbial activity was not measured in the present study. The results also support those of **Zhihui *et al.* (2016)**, who reported that the use of synthetic and organic fertilizers together increased phosphorus uptake in maize substantially. The findings suggest that Azolla may contribute to nutrient management while potentially reducing the need for synthetic phosphorus inputs under the conditions evaluated.

T2 also had the highest potassium levels (350.1 kg/ha), supporting the idea that synthetic fertilizers had a considerable impact on the availability of potassium in the soil. While treatment T6 (50% NPK + 50% Azolla) had lower potassium levels than 100% NPK (274.1 kg/ha) when compared to other treatments that contained Azolla, T5 (Azolla only) had very low potassium levels (26.5 kg/ha). Consequently, Azolla is not a major source of potassium **(Yahaya *et al.* 2023)**, and organic fertilizers often do not provide adequate amounts of potassium for balanced nutrient management.

The results of the present study showed significant differences in plant growth parameters among the treatments. The highest plant height was observed in T6 (50% NPK + 50% Azolla), followed by T7 (70% NPK + 30% Azolla) and T2 (100% NPK). This suggests that the combination of Azolla and synthetic fertilizers provided a balanced nutrient supply that supported vegetative growth. The improved growth observed under combined treatments may be associated with the complementary nutrient contribution from both organic and synthetic sources. However, because soil microbial activity, nutrient mineralization and soil organic matter changes were not measured in the present study, the mechanisms underlying the observed growth responses cannot be confirmed.

The number of fruits per plant also varied significantly among treatments. T6 recorded the highest number of fruits per plant, followed by T2 and T5, whereas the control recorded the lowest value. This indicates that integrated nutrient applications may support reproductive development under the conditions of the present experiment. However, fruit number represents a yield component and should not be interpreted as cumulative crop yield.

Average fruit weight was highest in T5, followed by T6 and T7, while the control recorded the lowest value. The higher fruit weight observed under Azolla-containing treatments may be associated with the gradual availability of nutrients from the biomass. Nevertheless, since cumulative fruit yield per plant or per unit area was not measured, the present study does not establish that any treatment increased or maintained total tomato yield.

Nutrient uptake further demonstrated differences among treatments. T8 (40% NPK + 60% DAB) recorded the highest numerical nitrogen uptake (146 kg ha^{-1}), followed by T5 (145.8 kg ha^{-1}), whereas T2 (100% NPK) recorded 139.2 kg ha^{-1}. The relatively high nitrogen uptake in DAB-containing treatments suggests that the DAB supplied a substantial amount of nitrogen to the crop. However, nitrogen uptake and nitrogen-use efficiency represent different measures, and the observed nitrogen uptake should be interpreted together with the calculated NUE. The gradual release of nitrogen from decomposing DAB may have contributed to its availability during crop development, but nitrogen mineralization and losses were not measured and therefore this mechanism remains a possible explanation rather than a demonstrated effect.

The broader Integrated Nutrient Management (INM) literature supports this approach. **Liu *et al.* (2021)** reported that appropriate combinations of organic and synthetic nitrogen sources in vegetable systems could improve yield while reducing nitrogen losses and increasing soil organic carbon compared with synthetic nitrogen alone. Similarly, **Hayat *et al.* (2026)** reported from a global meta-analysis that combined DAB and NPK generally produced stronger yield responses than either DAB or NPK alone, although vegetable-specific evidence was comparatively limited. These studies provide a useful framework for interpreting the present findings, but their reported effects on nitrogen leaching, greenhouse-gas emissions and soil organic carbon cannot be attributed to the present experiment because these variables were not measured.

The present results do not support identifying a single treatment as universally superior. T7 produced the highest numerical LAI, T2 the highest numerical DMP, T6 the highest numerical plant height and fruit number, T5 the highest numerical average fruit weight, and T8 the highest numerical nitrogen uptake, while T2 recorded the highest P and K uptake. This variation demonstrates that the response to DAB–NPK combinations depended on the specific growth, yield-component or nutrient-uptake parameter considered. The integrated treatments, particularly T6 and T7, showed promising responses for selected growth and reproductive characteristics and indicated the potential of DAB as a component of INM.

CONCLUSION

The study was conducted as a short-duration pot experiment under common field conditions, and therefore the findings should be interpreted within the experimental context. Soil microbial activity, nutrient mineralization, nutrient leaching, greenhouse-gas emissions and long-term changes in soil organic carbon are not directly assessed. Consequently, mechanisms involving improved microbial activity, reduced nutrient losses or enhanced nutrient-use efficiency cannot be confirmed from the present data. Further field-based and multi-season studies should evaluate cumulative yield, NUE, soil-quality indicators and economic returns to determine the practical potential of DAB as a partial component of synthetic fertilizer management in tomato production.

The study's results indicate that using DAB in combination with synthetic fertilizers has significantly greater benefits on plant growth, yield components, and nutrient uptake than using only one type of fertilizer. The study's results indicate that using DAB in combination with synthetic fertilizers influenced plant growth, selected yield components, and nutrient uptake, although the response varied among treatments and measured parameters. The highest numerical values for individual parameters were observed under different treatments, with T7 recording the highest LAI, T2 the highest DMP, T6 the highest plant height and fruit number, T5 the highest average fruit weight, and T8 the highest nitrogen uptake, while T2 recorded the highest phosphorus and potassium uptake.

Future research should focus on the long-term effects of Azolla biomass-based fertilization on crop yields, soil quality, and environmental sustainability within multiple agroecosystems. If adopted as part of Integrated Nutrient Management systems, the utilization of Azolla provides a viable method to help diminish the adverse impacts of climate change on the agricultural industry while achieving worldwide food security.

REFERENCES

Addelman, S. (1969). The Generalized Randomized Block Design. The American Statistician. https://www.tandfonline.com/doi/abs/10.1080/00031305.1969.10481868

Ahmad, N., Virk, A. L., Hafeez, M. B., Ercisli, S., Golokhvast, K. S., Qi, Y., Guo, X., Zhang, Y., Wang, R., Wang, X., Rehmani, M. I. A., & Li, J. (2024). Effects of different tillage and residue management systems on soil organic carbon stock and grain yield of rice–wheat double cropping system. Ecological Indicators, 158, 111452. https://doi.org/10.1016/j.ecolind.2023.111452

Arora, A., Nandal, P., & Chaudhary, A. (2023). Critical evaluation of novel applications of aquatic weed Azolla as a sustainable feedstock for deriving bioenergy and feed supplement. Environmental Reviews, 31(2), 195–205. https://doi.org/10.1139/er-2022-0033

Asch, J., Johnson, K., Mondal, S., & Asch, F. (n.d.). Comprehensive assessment of extraction methods for plant tissue samples for determining sodium and potassium via flame photometer and chloride via automated flow analysis<link href='#jpln202100344-note-0001'>#</link>. https://doi.org/10.1002/jpln.202100344

Bai, Y.-C., Chang, Y.-Y., Hussain, M., Lu, B., Zhang, J.-P., Song, X.-B., Lei, X.-S., & Pei, D. (2020). Soil chemical and microbiological properties are changed by long-term chemical fertilizers that limit ecosystem functioning. Microorganisms, 8(5), 694.

Bai, Y.-C., Chang, Y.-Y., Hussain, M., Lu, B., Zhang, J.-P., Song, X.-B., Lei, X.-S., & Pei, D. (2020). Soil chemical and microbiological properties are changed by long-term chemical fertilizers that limit ecosystem functioning. Microorganisms, 8(5), 694.

Beltran-Peña, A., Rosa, L., & D'Odorico, P. (2020). Global food self-sufficiency in the 21st century under sustainable intensification of agriculture. Environmental Research Letters, 15(9), 095004. https://doi.org/10.1088/1748-9326/ab9388

Benevolenza, M. A., & DeRigne, L. (2019). The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. Journal of Human Behavior in the Social Environment, 29(2), 266–281. https://doi.org/10.1080/10911359.2018.1527739

Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. The Journal of Agricultural Science, 55(1), 11–33.

Gerszberg, A., Hnatuszko-Konka, K., Kowalczyk, T., & Kononowicz, A. K. (2015). Tomato (Solanum lycopersicum L.) in the service of biotechnology. Plant Cell, Tissue and Organ Culture (PCTOC), 120(3), 881-902.

Hayat, M., Sáez-Sandino, T., Wang, J., Li, J., Zhou, G. & Singh, B.K. (2026). Compost-based organic amendments and synthetic fertilisers enhance soil health and crop yield worldwide. Journal of Sustainable Agriculture and Environment, 5(2), e70157. https://doi.org/10.1002/sae2.70157

Heuvelink, E. (1995). Dry Matter Production in a Tomato Crop: Measurements and Simulation. Annals of Botany, 75(4), 369–379. https://doi.org/10.1006/anbo.1995.1035

Jackson, M. L. (1973). Soil Chemical Analysis,(2nd Indian Print) Prentice-Hall of India Pvt. Ltd. New Delhi, 38, 336.

John, D. A., & Babu, G. R. (2021). Lessons from the aftermaths of green revolution on food system and health. Frontiers in Sustainable Food Systems, 5, 644559.

Kumar, R., Kumar, R., & Prakash, O. (2019). Chapter-5 the impact of chemical fertilizers on our environment and ecosystem. Chief Ed, 35(69), 1173–1189.

Liu, B., Wang, X., Ma, L., Chadwick, D. & Chen, X. (2021). Combined applications of organic and synthetic nitrogen fertilizers for improving crop yield and reducing reactive nitrogen losses from China's vegetable systems: A meta-analysis. Environmental Pollution, 269, 116143. https://doi.org/10.1016/j.envpol.2020.116143

Maham, S. G., Rahimi, A., Subramanian, S., & Smith, D. L. (2020). The environmental impacts of organic greenhouse tomato production based on the nitrogen-fixing plant (Azolla). Journal of Cleaner Production, 245, 118679.

Marzouk, S. H., Tindwa, H. J., Amuri, N. A., & Semoka, J. M. (2023). An overview of underutilized benefits derived from Azolla as a promising biofertilizer

in lowland rice production. Heliyon, 9(1). https://www.cell.com/heliyon/fulltext/S2405-8440(23)00247-5
Marzouk, S. H., Tindwa, H. J., Amuri, N. A., Chande, H. H., & Semoka, J. M. (2024). Enhancing phosphorus use efficiency and soil quality indicators in lowland paddy ecosystem through Azolla, rice straw, and NPKS fertilizers. Frontiers in Agronomy, 6. https://doi.org/10.3389/fagro.2024.1376110
Murthy, R. K., Nagaraju, B., Govinda, K., Uday Kumar, S. N., Basavaraja, P. K., Saqeebulla, H. M., Gangamrutha, G. V., Srivastava, S., & Dey, P. (2024). Soil test crop response nutrient prescription equations for improving soil health and yield sustainability—A long-term study under Alfisols of southern India. Frontiers in Plant Science, 15. https://doi.org/10.3389/fpls.2024.1439523
Nagata, K., Yoshinaga, S., Takanashi, J., & Terao, T. (2001). Effects of Dry Matter Production, Translocation of Nonstructural Carbohydrates and Nitrogen Application on Grain Filling in Rice Cultivar Takanari, a Cultivar Bearing a Large Number of Spikelets. Plant Production Science, 4(3), 173–183. https://doi.org/10.1626/pps.4.173
Okolie, C. C., Danso-Abbeam, G., Groupson-Paul, O., & Ogundeji, A. A. (2022). Climate-smart agriculture amidst climate change to enhance agricultural production: A bibliometric analysis. Land, 12(1), 50.
Olsen, S. R., & Watanabe, F. S. (1957). A Method to Determine a Phosphorus Adsorption Maximum of Soils as Measured by the Langmuir Isotherm1. Soil Science Society of America Journal, 21(2), 144. https://doi.org/10.2136/sssaj1957.03615995002100020004x
Paramanik, B., Mahanta, S., Das, B., Patra, P. S., Choudhury, A., Ghatak, P., Layek, J., Dutta, G., Saikia, N., & Biswakarma, N. (2024). Enhancing rice productivity through holistic nutrient management: Integrating vermicompost and Azolla for improved agronomic performance and sustainability. Journal of Plant Nutrition, 47(17), 2866–2880. https://doi.org/10.1080/01904167.2024.2369075
Peterburgski, A. V., & Bodrova, I. M. (1958). Studies on root nutrition and physiology of plants infected by root-knot nematodes.
Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. PLOS ONE, 14(5), e0217148. https://doi.org/10.1371/journal.pone.0217148
Schleussner, C.-F., Pfleiderer, P., Andrijevic, M., Vogel, M. M., Otto, F. E. L., & Seneviratne, S. I. (2021). Pathways of climate resilience over the 21st century. Environmental Research Letters, 16(5), 054058. https://doi.org/10.1088/1748-9326/abed79
Schnitter, R., & Berry, P. (2019). The climate change, food security and human health nexus in Canada: A framework to protect population health. International Journal of Environmental Research and Public Health, 16(14), 2531.
Seleiman, M. F., Elshayb, O. M., Nada, A. M., El-leithy, S. A., Baz, L., Alhammad, B. A., & Mahdi, A. H. A. (2022). Azolla Compost as an Approach for Enhancing Growth, Productivity and Nutrient Uptake of Oryza sativa L. Agronomy, 12(2), Article 2. https://doi.org/10.3390/agronomy12020416
Setiawati, M. R., Damayani, M., Herdiyantoro, D., Suryatmana, P., Anggraini, D., & Khumairah, F. H. (2018). The application dosage of A. pinnata in fresh and powder form as organic fertilizer on soil chemical properties, growth and yield of rice plant. AIP Conference Proceedings, 1927(1), 030017. https://doi.org/10.1063/1.5021210
Thapa, P., & Poudel, K. (2021). Azolla: Potential biofertilizer for increasing rice productivity, and government policy for implementation. Journal of Wastes and Biomass Management, 3(2), 62–68.
Ting, J. Y., Kamaruddin, N. A., & Mohamad, S. S. S. (2022). Nutritional evaluation of Azolla pinnata and Azolla microphylla as feed supplements for dairy ruminants. Journal of Agrobiotechnology, 13(1S), 17–23.
Tiwari, J. K., Behera, T. K., Rai, N., Yerasu, S. R., Singh, M. K., & Singh, P. M. (2022). Tomato breeding for processing in India: Current status and prospects. Vegetable Science, 49(02), 123-132.
Wieczorek, D., Żyszka-Haberecht, B., Kafka, A., & Lipok, J. (2022). Determination of phosphorus compounds in plant tissues: From colourimetry to advanced instrumental analytical chemistry. Plant Methods, 18(1), 22. https://doi.org/10.1186/s13007-022-00854-6
Yadav, R. K., Abraham, G., Singh, Y. V., & Singh, P. K. (2014). Advancements in the utilization of Azolla-Anabaena system in relation to sustainable agricultural practices. Proc. Indian Natl. Sci. Acad, 80(2), 301–316. h
Yahaya, S. M., Mahmud, A. A., Abdullahi, M., & Haruna, A. (2023). Recent advances in the chemistry of nitrogen, phosphorus and potassium as fertilizers in soil: A review. Pedosphere, 33(3), 385–406.
Yang, G., Ji, H., Liu, H., Feng, Y., Zhang, Y., Chen, L., & Guo, Z. (2021). Nitrogen fertilizer reduction in combination with Azolla cover for reducing ammonia volatilization and improving nitrogen use efficiency of rice. PeerJ, 9, e11077. https://doi.org/10.7717/peerj.11077
Yao, Y., Zhang, M., Tian, Y., Zhao, M., Zeng, K., Zhang, B., Zhao, M., & Yin, B. (2018). Azolla biofertilizer for improving low nitrogen use efficiency in an intensive rice cropping system. Field Crops Research, 216, 158–164. https://doi.org/10.1016/j.fcr.2017.11.020
Zeleke, Y. G., Haile, A., Kiflu, A., & Alemayehu, H. (2024). Morphological and physiological plasticity of tomato in response to Azolla fern, a novel organic fertilizer of environmentally friendliness. Heliyon, 10(20). https://doi.org/10.1016/j.heliyon.2024.e39110
Zeleke, Y.G., Haile, A., Kiflu, A., *et al.* (2024). Improving marketable yield and phytochemical characteristics of N-fertilized tomato fruits with soil organic amendments through Azolla. International Journal of Vegetable Science, 30(3), 294–310. https://doi.org/10.1080/19315260.2024.2360580
Zhihui, W. E. N., Jianbo, S., Blackwell, M., Haigang, L. I., Bingqiang, Z., & Huimin, Y. (2016). Combined applications of nitrogen and phosphorus fertilizers with manure increase maize yield and nutrient uptake via stimulating root growth in a long-term experiment. Pedosphere, 26(1), 62–73.