Biostimulant effects of Spirulina platensis and Azolla pinnata on growth, flowering, and quality of Polianthes tuberose L. under NFT hydroponics

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Abstract

Tuberose (*Polianthes tuberosa* L.) production faces increasing constraints from soil degradation, inefficient fertilizer use, and rising production costs, while sustainable nutrient management strategies for soilless floriculture remain insufficiently explored. This study investigated whether partial substitution of mineral fertilization with algal biostimulants could improve productivity and economic efficiency of tuberose under a vertical nutrient film technique hydroponic system. During the 2023 and 2024 growing seasons, mineral nutrition, bio-based extracts of *Azolla pinnata* and *Spirulina platensis*, and integrated treatments combining algal extracts with 50% mineral nutrition were evaluated using palm bark as a local substrate. Growth, flowering, postharvest quality, bulb productivity, nutrient status, and economic feasibility were assessed. Significant treatment effects were observed for all major parameters. Integrated nutrient treatments outperformed full mineral nutrition and sole bio-based inputs. *Spirulina platensis* + 50% mineral treatment produced the highest stem yield of 94 stems compared with 86 under full mineral nutrition, and achieved the greatest net return of 88.98 USD, the highest return on variable cost of 3.74, and the lowest break-even price of 0.25 USD per stem. While, *Azolla pinnata* + 50% mineral treatment ranked second in addition improving productivity and profitability. Although, sole bio-based treatments reduced variable costs, they were less effective in maximizing yield and returns than integrated strategies. These findings demonstrate that partial mineral substitution with algal biostimulants in NFT hydroponics improves nutrient use efficiency, enhances flower production and economic performance, and provides a sustainable strategy for resource-efficient tuberose cultivation.

1. Introduction

Tuberose (*Polianthes tuberosa* L.) is a high-value ornamental bulb crop widely cultivated for cut flowers and essential oil production due to its strong fragrance, extended vase life, and high market demand (Archana et al., 2019). However, sustaining yield and quality under conventional soil-based systems has become increasingly challenging due to soil degradation, water scarcity, climate variability, and rising input costs (Găgeanu et al., 2024). These constraints have accelerated the adoption of controlled-environment and soilless cultivation systems as more resource-efficient and sustainable alternatives. Hydroponic systems, particularly the Nutrient Film Technique (NFT), offer precise control over nutrient supply, improved water-use efficiency, and reduced incidence of soil-borne diseases, making them highly suitable for high-value floricultural crops (Mukhtar et al., 2022). Despite these advantages, the economic sustainability of hydroponic production remains strongly dependent on optimizing input use, especially mineral fertilizers, which constitute a major proportion of production costs (Chaube et al., 2022). Enhancing nutrient use efficiency alongside reducing mineral fertilizer inputs is now a critical priority for advancing sustainable agricultural production. Bio-based stimulants derived from algae have emerged as promising tools for enhancing plant performance under soilless systems. *Azolla pinnata*, through its symbiotic association with nitrogen-fixing cyanobacteria, contributes to increased nutrient availability and improved plant growth, while its biochemical composition supports its application as a biofertilizer (Schluepmann et al., 2021). Similarly, *Spirulina platensis* is rich in amino acids, micronutrients, and growth-promoting substances that have been shown to enhance nutrient uptake, chlorophyll synthesis, and overall plant productivity in hydroponic conditions (Abdel-Rahman et al., 2023). These bioactive compounds are believed to improve physiological processes such as photosynthetic efficiency and nutrient assimilation, thereby increasing nutrient use efficiency.

In parallel, the use of sustainable and locally available substrates such as palm bark has gained attention as an alternative to peat-based media, contributing to improved root aeration and nutrient dynamics while reducing environmental impact (Rosli et al., 2023). However, while individual applications of hydroponic systems, algal biostimulants, and alternative substrates have been widely studied, their integrated effects particularly under vertical NFT systems remain insufficiently explored, especially in relation to both agronomic performance and economic feasibility in ornamental crops such as tuberose. Therefore, this study aims to evaluate the effects of partial substitution of mineral fertilizers with *Spirulina platensis* and *Azolla pinnata* under a vertical NFT hydroponic system on growth, flowering, nutrient status, and economic return of tuberose. By integrating agronomic and economic analyses, this work seeks to provide a comprehensive assessment of sustainable nutrient management strategies for high-value floriculture production.

2. Results

Analysis of variance revealed significant differences among nutrient treatments for most measured parameters.

2.1. Vegetative growth

Vegetative growth of *Polianthes tuberosa* was significantly influenced by nutrient solution composition in both seasons (Table 1). All vegetative traits showed significant differences among treatments at $P \leq 0.05$. Among mineral treatments, Hoagland solution resulted in higher vegetative growth compared with the MS nutrient solution. However, the integration of bio-based extracts with mineral nutrition markedly enhanced plant performance under NFT conditions.

The integrated treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) produced the highest vegetative growth across both seasons. Plant height reached 47.78 and 48.11 cm, compared with lower values in mineral-only treatments. Similarly, T7 resulted in the highest leaf number (54.83 and 56.26 leaves.plant^{-1}) and leaf area (112.04 and 114.78 cm^2.plant^{-1}). Biomass accumulation was also maximized under this treatment, with leaf fresh weight reaching 97.42 and 100.59 g plant^{-1} and leaf dry weight 17.26 and 20.89 g.plant^{-1}. Total plant fresh weight reached 199.71 and 204.00 g.plant^{-1}, while plant dry weight reached 32.41 and 34.33 g.plant^{-1}.

The integrated treatment with *Azolla pinnata* and 50% Hoagland solution (T5) ranked second, with total plant fresh weights of 168.74 and 174.30 g plant^{-1} and dry weights of 26.04 and 28.96 g plant^{-1}. The sole application of *Spirulina platensis* (T6) also improved vegetative growth compared with mineral treatments, although to a lesser extent than integrated strategies.

Table 1
Effect of different nutrient solution treatments on vegetative growth parameters of Polianthes tuberosa L. under NFT hydroponic system during two growing seasons (2022/2023 and 2023/2024)

Treatments		Plant height at flowering stage (cm)		Number of leaves at 1st spike Emergence		leaf area/plant (cm^2)		leaves fresh weights/plant (g)		leaves dry weights/plant (g)		Plant fresh weight (g)		Plant dry weight (g)	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
T1	Hoagland's solution (Control)	40.00	41.23	40.33	42.67	85.67	87.42	78.70	82.26	12.44	14.27	127.97	129.30	17.80	19.66
T2	MS nutrient solution	41.78	42.76	44.49	45.00	89.59	92.82	83.55	84.29	13.06	16.29	133.14	135.29	21.24	24.30
T3	Hoagland 75% + MS 25%	42.00	42.78	45.89	46.67	98.52	102.63	86.09	88.08	14.19	17.24	141.11	145.29	23.06	25.33
T4	A. pinnata	43.76	44.00	47.67	48.29	100.65	105.71	87.78	89.77	15.19	17.60	155.04	164.29	24.03	26.30
T5	A. pinnata + Hoagland 50%	45.23	45.89	48.90	50.39	105.18	107.67	89.89	93.22	15.62	18.30	168.74	174.30	26.04	28.96
T6	S. platensis	46.89	47.87	49.71	53.30	109.04	112.63	94.63	95.27	16.11	19.52	188.05	193.29	28.49	31.25
T7	S. platensis + Hoagland 50%	47.78	48.11	54.83	56.26	112.04	114.78	97.42	100.59	17.26	20.89	199.71	204.00	32.41	34.33
Mean		43.92	44.66	47.40	48.94	100.10	103.38	88.29	90.50	14.84	17.73	159.11	163.68	24.72	27.16
L.S.D at 0.05		3.54	3.32	1.77	1.12	1.56	1.12	1.21	1.20	1.46	2.05	3.67	3.03	2.57	2.59

2.2. Flowering time and spike characteristics

Table 2. Effect of different nutrient solutions on flowering time and spike characteristics of *Polianthes tuberosa* L. under NFT hydroponic conditions during two growing seasons.

Treatments		Number of days to flowering (days)		Spike Length (cm)		Spike fresh weight (g)		Spike dry Weight (g)		Spike diameter (mm)	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
T1	Hoagland's solution (Control)	97.04	103.15	61.11	63.37	45.08	47.30	11.92	14.56	7.04	7.28
T2	MS nutrient solution	94.04	97.29	64.15	66.11	52.22	53.30	14.88	16.93	8.31	9.08
T3	Hoagland 75% + MS 25%	85.08	88.08	69.29	70.22	55.00	57.01	21.02	24.15	8.63	9.62
T4	A. pinnata	81.71	84.92	74.08	76.05	67.67	69.04	24.04	26.01	8.70	9.82
T5	A. pinnata + Hoagland 50%	77.20	78.26	77.26	79.03	74.63	73.29	26.25	28.19	9.07	10.15
T6	S. platensis	74.04	76.53	79.26	82.06	88.75	93.04	27.68	32.07	9.29	10.42
T7	S. platensis + Hoagland 50%	71.07	73.04	84.27	85.39	96.96	97.77	31.04	33.64	9.83	10.62
Mean		82.88	85.90	72.77	74.61	68.62	70.11	22.41	25.08	8.70	9.57
L.S.D at 0.05		1.84	1.99	1.61	2.36	6.03	6.66	1.52	1.54	0.24	0.28

Flowering time and spike characteristics were significantly affected by nutrient solution composition in both seasons. The integrated treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) produced the best flowering performance across both seasons. This treatment resulted in the earliest flowering (71.07 and 73.04 days), compared with longer durations under mineral treatments. It also produced the longest spikes (84.27 and 85.39 cm), the highest spike fresh weights (96.96 and 97.77 g), and the greatest spike dry weights (31.04 and 33.64 g). Spike diameter was also maximized under T7, reaching 9.83 and 10.62 mm. Representative visual differences in flowering performance among nutrient treatments are presented in Fig. 1, supporting the quantitative responses observed in Table 2.

The sole application of *Spirulina platensis* (T6) ranked second for most flowering traits, producing spike lengths of 79.26 and 82.06 cm and spike fresh weights of 88.75 and 93.04 g. Similarly, the integrated treatment with *Azolla pinnata* and 50% Hoagland solution (T5) significantly improved flowering performance compared with mineral treatments, with spike lengths of 77.26 and 79.03 cm and spike fresh weights of 74.63 and 73.29 g. In contrast, the control treatment (full Hoagland solution) resulted in the longest time to flowering and the lowest spike quality parameters.

2.3. Floret traits, postharvest quality, and vase life

Significant differences among treatments were observed for floret characteristics and postharvest performance of tuberose flowers in both seasons, as presented in Table 3.

The integrated treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) produced the highest floral quality and postharvest performance. Flowering duration reached 28.08 and 26.05 days, while the number of florets per spike increased to 20.33 and 19.11. Floret size was also maximized under T7, with floret length reaching 7.34 and 7.45 cm and floret diameter 5.56 and 6.06 cm.

Figure 1. Representative growth and flowering responses of tuberose under mineral nutrition and biostimulant treatments in the NFT hydroponic system: (a) NFT system overview; (b) Hoagland's solution (control); (c) Hoagland 75% + MS 25%; (d) Azolla pinnata + Hoagland 50%; (e) Spirulina platensis + Hoagland 50%.

Postharvest quality index was highest under T7 (99.00 and 98.33), and vase life reached 8.36 and 9.62 days, compared with shorter vase life in the control treatment (6.13 and 6.39 days). The sole application of *Spirulina platensis* (T6) ranked second for most postharvest traits, followed by the integrated treatment with *Azolla pinnata* and Hoagland solution (T5).

2.4. Bulb yield and root characteristics

Bulb productivity and root development were significantly affected by nutrient treatments in both seasons (Table 4). The integrated treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) produced the highest values for most bulb and root traits. This treatment resulted in the greatest number of new bulblets (22.31 and 22.23 bulblets plant^{-1}), the highest bulblet fresh weight (3.50 and 3.49 g), and the largest clump circumference (9.77 and 9.91 cm). In addition, the fresh weight of the main bulb reached 40.27 and 42.95 g under T7. Root length was also maximized, reaching 27.36 and 27.44 cm.

The sole application of *Spirulina platensis* (T6) ranked second, showing higher values than mineral treatments for most bulb and root parameters. Similarly, the integrated treatment with *Azolla pinnata* and 50% Hoagland solution (T5) improved bulb productivity compared with mineral treatments. In contrast, the control treatment (full Hoagland solution, T1) recorded the lowest values for most bulb and root traits.

Table 3
Effect of nutrient solution composition on floret traits and postharvest performance of Polianthes tuberosa L. under an NFT hydroponic system during two growing seasons.

Treatments		Duration of flowering (days)		Number of florets/ spike		Length of floret (cm)		Diameter of floret (cm)		Postharvest quality		Vase life (days)	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
T1	Hoagland's solution (Control)	14.37	16.66	10.11	11.97	5.11	5.31	4.16	4.43	73.74	75.99	6.13	6.39
T2	MS nutrient solution	16.28	18.30	11.32	13.00	6.13	6.34	4.43	5.03	86.08	85.33	6.25	7.39
T3	Hoagland 75% + MS 25%	18.29	19.31	12.30	14.01	6.41	6.69	5.11	5.24	90.00	89.04	6.60	7.63
T4	A. pinnata	18.48	19.72	13.48	15.22	6.48	6.92	5.21	5.47	92.11	92.22	7.09	8.18
T5	A. pinnata + Hoagland 50%	20.34	22.33	14.44	17.04	6.56	7.01	5.25	5.72	94.30	93.00	7.50	8.62
T6	S. platensis	24.36	23.30	15.35	17.78	6.88	7.18	5.32	5.82	97.22	94.96	8.13	9.04
T7	S. platensis + Hoagland 50%	28.08	26.05	20.33	19.11	7.34	7.45	5.56	6.06	99.00	98.33	8.36	9.62
Mean		20.03	20.81	13.90	15.45	6.42	6.70	5.01	5.40	90.35	89.84	7.15	8.12
L.S.D at 0.05		0.74	0.89	0.87	1.59	0.19	0.21	0.12	0.24	2.01	2.68	0.11	0.21

Table 4
Effect of different nutrient solution treatments on bulb productivity and root traits of Polianthes tuberosa L. grown under an NFT hydroponic system during two successive seasons (2022/2023 and 2023/2024).

Treatments		Number of new bulblets / plant		Fresh weight of bulblets (g)		Clump Circumference (cm)		Fresh weight of main bulb (g)		Root length(cm)	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
T1	Hoagland's solution (Control)	13.61	13.92	2.25	2.52	5.75	5.47	23.97	25.41	14.78	13.49
T2	MS nutrient solution	16.40	16.33	2.61	2.64	7.40	7.51	28.06	28.47	16.31	16.28
T3	Hoagland 75% + MS 25%	17.77	17.22	2.82	2.89	8.11	8.27	30.20	31.55	18.26	18.49
T4	A. pinnata	18.55	18.27	3.04	3.08	8.22	8.62	33.08	33.55	19.37	19.56
T5	A. pinnata + Hoagland 50%	20.06	19.26	3.20	3.13	9.33	9.75	37.17	38.07	21.23	21.53
T6	S. platensis	20.34	20.29	3.39	3.30	9.56	9.67	38.40	39.52	24.06	24.44
T7	S. platensis + Hoagland 50%	22.31	22.23	3.50	3.49	9.77	9.91	40.27	42.95	27.36	27.44
Mean		18.43	18.22	2.97	3.01	8.31	8.46	33.02	34.22	20.20	20.18
L.S.D at 0.05		1.16	1.23	0.16	0.11	1.09	1.17	1.16	1.07	1.42	1.13

2.5. Photosynthetic pigments, carbohydrate content, and macronutrient composition

Nutrient treatments significantly affected photosynthetic pigments, carbohydrate content, and macronutrient composition (N, P, and K) in tuberose plants across both seasons (Table 5).

The integrated treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) recorded the highest values for all measured physiological and biochemical parameters. Chlorophyll a reached 1.21 and 1.10 mg g^{-1} f.w., while chlorophyll b reached 0.76 and 0.78 mg g^{-1} f.w. Carotenoid content also increased under T7, reaching 0.69 and 0.70 mg g^{-1} f.w.

Total carbohydrate content was highest under T7 (31.48% and 31.20%). Similarly, macronutrient concentrations were maximized under this treatment, with nitrogen reaching 2.18 and 2.14%, phosphorus 0.57 and 0.58%, and potassium 2.10 and 2.11%.

The sole application of *Spirulina platensis* (T6) and treatments involving *Azolla pinnata* also improved biochemical traits compared with mineral treatments, although to a lesser extent than integrated strategies. In contrast, Hoagland and MS treatments alone resulted in lower pigment concentrations and nutrient contents.

Table 5. Effect of hydroponic nutrient treatments on photosynthetic pigments, carbohydrate content, and macronutrient composition of *Polianthes tuberosa* L. during two successive growing seasons (2022/2023 and 2023/2024).

Treatments		Chlorophyll-a (mg/ g f.w)		Chlorophyll-b (mg/ g f.w.)		Carotenoids (mg/ g f.w.)		Total carbohydrates (%)		N %		P %		K %	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
T1	Hoagland's solution (Control)	0.85	0.87	0.60	0.61	0.61	0.62	24.38	24.60	1.88	1.90	0.39	0.41	1.73	1.75
T2	MS nutrient solution	0.89	0.90	0.63	0.64	0.63	0.64	26.80	26.95	1.94	1.96	0.42	0.43	1.77	1.78
T3	Hoagland 75% + MS 25%	0.95	0.94	0.65	0.66	0.65	0.66	28.29	28.50	1.96	1.94	0.44	0.45	1.83	1.85
T4	A. pinnata	0.98	0.96	0.69	0.70	0.66	0.67	28.76	28.90	2.02	2.00	0.46	0.44	1.87	1.89
T5	A. pinnata + Hoagland 50%	1.05	1.00	0.72	0.73	0.67	0.68	29.56	29.40	2.05	2.08	0.50	0.52	1.93	1.96
T6	S. platensis	1.08	1.06	0.73	0.75	0.68	0.69	30.45	30.30	2.10	2.12	0.53	0.54	2.03	2.05
T7	S. platensis + Hoagland 50%	1.21	1.10	0.76	0.78	0.69	0.70	31.48	31.20	2.18	2.14	0.57	0.58	2.10	2.11
Mean		1.00	0.98	0.68	0.70	0.66	0.67	24.42	28.55	2.02	2.02	0.47	0.48	1.89	1.91
L.S.D at 0.05		0.22	0.20	0.10	0.12	0.05	0.06	4.22	4.10	0.18	0.19	0.11	0.12	0.34	0.35

2.6. Economic performance under NFT hydroponics

2.6.1. Cost structure

The initial capital investment of the NFT hydroponic system was considered constant across all treatments, as the same infrastructure was used throughout the experiment. Capital costs are typically distributed over the operational lifespan of the system, with only a proportion attributed to each production cycle. ince the hydroponic infrastructure was already established within the research facility, capital costs were treated as fixed and excluded from the economic analysis. This approach avoids overestimation of production costs under experimental conditions and provides a more realistic assessment of operational efficiency.

Accordingly, the economic evaluation focused on variable costs to better reflect treatment-related differences in resource use and financial performance (Palmitessa et al., 2024; Mishra et al., 2024; Verma et al., 2023).

2.6.2. Variable cost structure

Total variable costs for tuberose production included bulbs, electricity and system maintenance, temporary labor, packaging, transportation and distribution, nutrient solutions, and bio-based additives. Several cost components remained constant across treatments under uniform experimental conditions. The cost of planting bulbs was fixed at USD 10.21 per production cycle, while electricity and system maintenance, labor, packaging, and transportation accounted for USD 2.13, 3.65, 1.82, and 1.52, respectively. Variations in total variable costs among treatments were primarily associated with nutrient solution costs and the use of bio-based additives. Mineral nutrient treatments, including Hoagland solution (T1), MS solution (T2), and Hoagland 75% + MS 25% (T3), required USD 6.38 for nutrient solutions, resulting in a total variable cost of USD 25.71 per production unit. In contrast, treatments based solely on bio-based extracts (*Azolla pinnata*, T4, and *Spirulina platensis*, T6) eliminated mineral nutrient costs but required USD 1.30 for bio-additives, reducing the total variable cost to USD 20.63. Integrated treatments combining bio-based extracts with reduced mineral fertilization showed intermediate costs. The treatments *Azolla pinnata* + 50% Hoagland (T5) and *Spirulina platensis* + 50% Hoagland (T7) required USD 3.19 for mineral nutrients and USD 1.30 for bio-additives, resulting in total variable costs of USD 23.82.

2.6.3. Comparative economic performance

Clear differences in economic performance were observed among mineral, bio-based, and integrated nutrient strategies (Table 6).

Yield and revenue

The integrated treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) produced the highest yield (94 stems unit^{-1}) and revenue (USD 112.8). This was followed by *Azolla pinnata* + 50% Hoagland (T5), which produced 91 stems and USD 109.2.

Among mineral treatments, Hoagland solution (T1) and Hoagland 75% + MS 25% (T3) produced identical yields (86 stems) and revenues (USD 103.2), whereas MS solution alone (T2) resulted in lower values (82 stems and USD 98.4).

Net return

Net return followed a similar trend, with the highest value recorded under T7 (USD 88.98 cycle^{-1}), followed by T5 (USD 85.38). Mineral treatments showed intermediate values (USD 77.49 for T1 and T3, and USD 72.69 for T2). Among bio-based treatments, T4 recorded USD 74.17, while T6 showed the lowest net return (USD 71.77).

Break-even analysis

Break-even production ranged from 17.19 to 21.43 stems per 96 plants. The lowest break-even values were observed for bio-based treatments (T4 and T6), whereas mineral treatments (T1, T2, and T3) showed the highest values. Break-even price ranged from USD 0.25 to 0.31 per stem, with the lowest value recorded under T7 and the highest under T2.

Return on variable cost

Return on variable cost (RVC) ranged from 2.83 to 3.74. The highest value was obtained under T7 (3.74), followed by T4 (3.60) and T5 (3.58), whereas the MS treatment (T2) recorded the lowest value (2.83).

Table 6
Comparative economic evaluation of tuberose cultivated under mineral, bio-based, and integrated nutrient strategies in an NFT hydroponic system.

Treatments		Total Variable Costs (USD)	Assumed Yield (Stems)	Selling Price /Stem)	Revenue	Net Return (USD)	Break-Even Point (Stems / 96 Plants)	Production Surplus (Stems)	Return on Variable Cost (RVC)	Break-Even Price (USD/Stem)	Price Safety Margin (USD)
T1	Hoagland's solution (Control)	25.71	86	1.2	103.2	77.49	21.43	+ 64.58	3.01	0.30	+ 0.90
T2	MS nutrient solution	25.71	82	1.2	98.4	72.69	21.43	+ 60.58	2.83	0.31	+ 0.89
T3	Hoagland 75% + MS 25%	25.71	86	1.2	103.2	77.49	21.43	+ 64.58	3.01	0.30	+ 0.90
T4	Azolla pinnata	20.63	79	1.2	94.8	74.17	17.19	+ 61.81	3.60	0.26	+ 0.94
T5	Azolla pinnata + Hoagland 50%	23.82	91	1.2	109.2	85.38	19.85	+ 71.15	3.58	0.26	+ 0.94
T6	Spirulina platensis	20.63	77	1.2	92.4	71.77	17.19	+ 59.81	3.48	0.27	+ 0.93
T7	Spirulina platensis + Hoagland 50%	23.82	94	1.2	112.8	88.98	19.85	+ 74.15	3.74	0.25	+ 0.95

3. Discussion

The present findings demonstrate that integrated nutrient management under NFT hydroponic conditions plays a central role in regulating growth, flowering, and nutrient accumulation in tuberose. The use of palm bark as an inert substrate ensured that plant performance was primarily governed by the composition of the circulating nutrient solution, in agreement with the hydroponic concept that substrates function mainly as physical support rather than nutrient sources (Mattson and Heinrich, 2005).

The superior vegetative and flowering performance observed under Hoagland solution compared with MS medium reflects its more balanced macro- and micronutrient composition, which supports enhanced photosynthetic activity, assimilate production, and efficient translocation of carbohydrates to developing floral structures. This is consistent with the higher growth and flowering parameters recorded in the present study under mineral and integrated nutrient treatments. Similar responses have been reported in ornamental crops such as *Lilium* (Barnes et al., 2010), gladiolus (Wahome et al., 2010), chrysanthemum (Thakur, 2016), and Asiatic hybrid lily (Asker, 2015), highlighting the critical role of balanced mineral nutrition in optimizing plant performance under soilless systems.

In tuberose, the relatively limited nutrient reserves in the mother bulb necessitate a continuous and well-balanced nutrient supply through fertigation to sustain vegetative growth and ensure successful floral initiation (Saqib et al., 2006). The enhanced performance observed under optimized nutrient regimes in the present study further supports the importance of external nutrient availability in compensating for the limited endogenous reserves of the bulb.

The improvements observed in spike length, floret number, and vase life under Hoagland nutrition can be attributed to enhanced water uptake, increased chlorophyll content, and improved carbohydrate availability for reproductive development (Kaur et al., 2016). These responses are consistent with the higher flowering and postharvest performance recorded in the present study under mineral and integrated nutrient regimes.

Despite the strong performance of Hoagland solution, the integrated application of *Spirulina platensis* and *Azolla pinnata* extracts with reduced mineral fertilization resulted in the highest overall plant performance, particularly under T7, indicating a biostimulatory effect rather than simple nutrient supplementation. This is supported by the superior vegetative growth, flowering traits, and postharvest longevity observed under integrated treatments compared with both mineral and sole bio-based applications.

Microalgal extracts are known to contain bioactive compounds such as amino acids, vitamins, phenolics, and phytohormone-like substances that stimulate root development, enhance chlorophyll biosynthesis, and improve metabolic efficiency (Shanab et al., 2012). Similarly, *Azolla pinnata* extract provides organic nutrients and biologically active compounds that enhance physiological processes and nutrient uptake (Yao et al., 2018). The combined effect of these compounds likely contributed to the improved photosynthetic performance, biomass accumulation, and nutrient status observed in the present study.

Importantly, the superior performance of integrated treatments under reduced mineral fertilization reflects improved nutrient-use efficiency rather than increased nutrient input. In the present study, partial substitution of mineral fertilizers by approximately 50% maintained or enhanced productivity under NFT conditions, demonstrating the potential of biostimulants to reduce dependence on synthetic fertilizers while sustaining high yield and quality. This finding is consistent with previous reports highlighting the role of biostimulants in improving nutrient efficiency and crop performance under soilless systems (Rouphael and Colla, 2009; Savvas and Gruda, 2018).

The enhanced bulb size, bulblet formation, and root development observed under NFT conditions, particularly under integrated treatments (T7 and T5), are consistent with improved nutrient availability and root-zone aeration associated with continuous nutrient flow. These conditions promote cell division and carbohydrate accumulation in storage organs, contributing to increased bulb productivity.

Hydroponic systems maintain nutrients in readily available forms and minimize losses, thereby enhancing nutrient uptake efficiency and biomass accumulation. This is reflected in the higher bulb weight and root development recorded in the present study under integrated and mineral nutrient treatments. Similar responses have been reported in ornamental crops grown under soilless conditions (Dufour and Guérin, 2005; Zheng et al., 2005; Rouphael and Colla, 2009).

The higher concentrations of nitrogen, phosphorus, and potassium observed under Hoagland and integrated treatments indicate improved nutrient assimilation under balanced nutrient supply and optimal root-zone conditions. Adequate nitrogen availability promotes biomass accumulation while maintaining the balance between vegetative and reproductive growth (Goins et al., 2004), whereas balanced NPK nutrition enhances flower yield and quality in ornamental crops (Mukhtar et al., 2022). These findings are consistent with the increased growth, flowering performance, and bulb development recorded under T7 in the present study.

Maintaining nutrient solution pH (5.8–6.2) and electrical conductivity within optimal ranges further supported nutrient availability and uptake efficiency, contributing to improved plant nutritional status and biochemical composition under NFT conditions (Brar et al., 2024).

From an economic perspective, integrated nutrient strategies clearly outperformed conventional mineral fertilization. The treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) produced the highest yield, net return, return on variable cost, and price safety margin, confirming its superior economic performance under NFT conditions.

Although sole bio-based treatments reduced production costs, maximum economic efficiency was achieved when biological inputs were combined with reduced mineral fertilization. This indicates that microalgae-based biostimulants primarily enhance nutrient-use efficiency rather than fully replacing mineral fertilizers (Colla and Rouphael, 2020; Yakhin et al., 2017).

The lower break-even price observed under integrated treatments further reflects improved economic resilience to market fluctuations, which is particularly important for commercial floriculture systems.

4. Materials and Methods

4.1. Experimental aim and location

This study evaluated sustainable production of tuberose (*Polianthes tuberosa* L.) under a vertical Nutrient Film Technique (NFT) hydroponic system through partial substitution (50%) of mineral fertilizers with bio-based extracts derived from *Azolla pinnata* and *Spirulina platensis*. A locally sourced palm bark substrate was used as a sustainable alternative to peat moss. Treatments included full-strength Hoagland solution, Murashige and Skoog (MS) nutrient solution, and integrated nutrient strategies combining mineral and bio-based inputs.

The experiment was conducted during the 2023 and 2024 growing seasons at the Hydroponic and Algae Research and Production greenhouse, Soil, Water and Environment Research Institute (SWERI), Agricultural Research Center (ARC), Giza, Egypt.

4.2. Plant material and NFT system

Uniform tuberose bulbs (8–9 cm circumference; 6–7 g fresh weight) were transplanted on 15 March into a vertical NFT hydroponic system. Bulbs were placed in perforated plastic cups filled with palm bark substrate to provide physical support and root aeration.

Nutrient solutions (Hoagland No. 2 and modified MS formulations) were continuously circulated through NFT channels to maintain a uniform and uninterrupted nutrient supply. The system was operated under standard greenhouse conditions (Fig. 2).

4.3. Preparation of *Spirulina platensis* extract

The *Spirulina platensis* strain (HSSASE5) was obtained from the Soil, Water and Environment Research Institute (SWERI), ARC, Giza, Egypt, and originally isolated from Wadi El-Natrun, Egypt. The strain was cultivated in Zarrouk's medium (Zarrouk, 1966) under continuous illumination (3500 lux) at 28 ± 2°C. Identification was confirmed morphologically and by 16S rRNA gene sequencing (GenBank accession no. KT277788.1; Mostafa et al., 2024). Fresh biomass harvested at the logarithmic growth phase was homogenized with tap water and filtered to obtain an aqueous extract. The extract was diluted to 10% (v/v) prior to application.

4.4. Preparation of *Azolla pinnata* extract

Fresh biomass of *Azolla pinnata* (1 kg) was obtained from SWERI, ARC, Giza, Egypt, and maintained in Yoshida medium (Yoshida et al., 1976). The biomass was homogenized with 1 L of water, filtered, and stored at 4°C as a stock extract (Taha and El-Shahat, 2017). Prior to application, the extract was diluted to 5% (v/v). The chemical composition of the extract was determined according to AOAC (1970), including crude protein (2.50%), crude fiber (1.40%), lipids

(0.35%), carbohydrates (4.00%), and ash (1.80%). Mineral content included N (0.40%), P (0.08%), K (0.17%), Ca (0.12%), Fe (200 ppm), Mn (25 ppm), Zn (6 ppm), and Cu (1.20 ppm).

4.5. Nutrient solution preparation, treatments, and experimental design

Nutrient solutions were prepared weekly using tap water (EC ≈ 0.45 dS m^{-1}; pH 7.01) and left overnight to allow chlorine dissipation. Seven nutrient treatments were evaluated under the NFT hydroponic system. The mineral treatments comprised: T1, full-strength Hoagland No. 2 solution (100%), which served as the control; T2, full-strength modified Murashige and Skoog (MS) nutrient solution (100%); and T3, an integrated mineral treatment consisting of 75% Hoagland solution + 25% MS medium (Lincoln and Zeiger, 2010; Murashige and Skoog, 1962; Eissa et al., 2019). The bio-based treatments comprised: T4, Azolla pinnata aqueous extract (5%, v/v); and T6, Spirulina platensis aqueous extract (10%, v/v). The integrated bio–mineral treatments comprised: T5, Azolla extract (5%, v/v) combined with 50% Hoagland solution; and T7, Spirulina extract (10%, v/v) combined with 50% Hoagland solution, where the bio-based extracts partially replaced 50% of the mineral nutrients. Nutrient solutions were maintained at pH 5.8–6.2 and electrical conductivity (EC) of 1.6–2.0 dS m^{-1} throughout the experiment. The experiment was arranged in a completely randomized design (CRD) with seven treatments. Each treatment was applied to an independent NFT channel containing nine plants, with three replicates per treatment (n = 27 plants per treatment). Nutrient solution was supplied at a rate of 2–3 L $week^{-1}$. The composition and description of all treatments are summarized in Fig. 3.

1. **Growth, flowering, and biochemical measurements**
2. Morphological, physiological, flowering, postharvest, and biochemical parameters were assessed as follows:

4.7.1. Vegetative growth

Plant height, leaf number, leaf area (Model 3100 area meter), leaf fresh and dry weights, and total plant fresh and dry weights were recorded. Dry weights were determined after oven-drying at 70°C to constant weight.

4.7.2. Flowering and inflorescence traits

Days to flowering, stem diameter, bud length, spike length and diameter, number of florets per spike, spike fresh weight, and vase life were recorded. Vase life was evaluated under controlled conditions (22 ± 2°C; 60–70% relative humidity; 12-h photoperiod) following Hassan et al. (2020).

4.7.3. Bulb and root traits

Bulb diameter, bulb fresh weight, bulblet number, root length, and root fresh weight were measured 16 weeks after planting.

4.7.4. Physiological measurements

Chlorophyll a, chlorophyll b, and total chlorophyll contents were determined spectrophotometrically according to Moran (1982).

4.7.5. Bulb chemical analysis

Dried bulb samples (70°C for 48 h) were analyzed for total nitrogen (Piper, 1947), phosphorus (Troug and Meyer, 1939), potassium (Brown and Lilliland, 1946), and total carbohydrates (DuBois et al., 1956).

4.8. Economic analysis

Economic performance was evaluated based on total variable costs, revenue, and profitability indicators. Net return was calculated as the difference between total revenue and total cost, while return on variable cost was calculated as the ratio of net return to total cost.

4.9. Statistical analysis

Data were analyzed using one-way analysis of variance (ANOVA) under a completely randomized design. Mean comparisons were performed using the least significant difference (LSD) test at $P \leq 0.05$, following Snedecor and Cochran (1980), using MSTAT software (1985).

5. Conclusion

Nutrient formulation and biological supplementation play a key role in regulating growth, flowering, bulb productivity, biochemical composition, and economic performance of tuberose under NFT hydroponic conditions. The integrated treatment combining *Spirulina platensis* with 50% Hoagland solution (T7) consistently produced superior performance, enhancing vegetative growth, flower quality, bulb yield, root development, and photosynthetic pigment content.The results demonstrate that mineral fertilization can be reduced by approximately 50% when combined with bio-based biostimulants without compromising productivity, indicating improved nutrient-use efficiency under integrated nutrient management. From an economic perspective, integrated treatments achieved the highest net return and profitability, while sole bio-based treatments showed greater production efficiency through higher return on variable cost and lower break-even price. These findings support the use of microalgal biostimulants in combination with reduced mineral fertilization as a practical and economically viable strategy for sustainable tuberose production under NFT hydroponic systems.

Declarations

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Author Contributions

Conceptualization: S.S.M.M., T.E.E., M.A.B., A.E.Sh., and W.M.A.; Methodology, S.S.M.M., T.E.E., W.M.A., M.S.M.M. and M.A.B.; Software, S.S.M.M., T.E.E., and M.A.B.; Formal analysis, S.S.M.M., W.M.A., A.E.Sh., M.S.M.M. and T.E.E.; Investigation, S.S.M.M., T.E.E., and A.E.Sh.; Resources, S.S.M.M., T.E.E., M.A.B., and W.M.A.; Writing original draft, S.S.M.M., T.E.E., M.S.M.M. and W.M.A.; Writing review & editing, S.S.M.M., T.E.E., and A.E.Sh.

All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Supplementary data

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Ethical approval statement: This study does not involve experiments involving human or animal.

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Figures

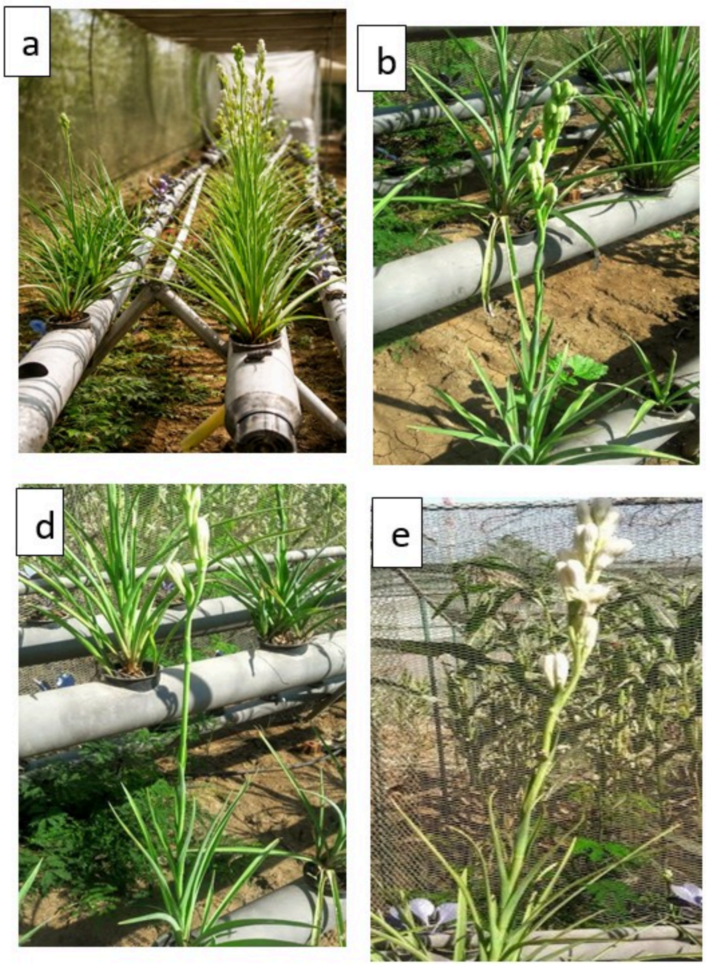

Figure 1. Representative growth and flowering responses of tuberose under mineral nutrition and biostimulant treatments in the NFT hydroponic system: (a) NFT system overview; (b) Hoagland's solution (control); (c) Hoagland 75% + MS 25%; (d) *Azolla pinnata* + Hoagland 50%; (e) *Spirulina platensis* + Hoagland 50%.

Figure 1

See image above for figure legend.

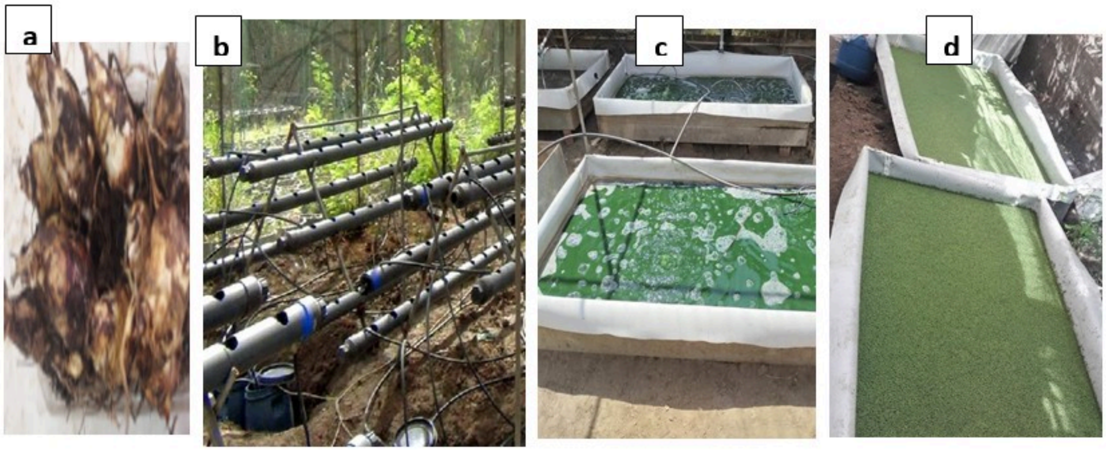

Figure 2. Experimental materials and vertical NFT hydroponic system used for tuberose cultivation, showing: (a) tuberose bulbs, (b) NFT channels, (c) mass culture of *Spirulina platensis*, and (d) mass culture of *Azolla pinnata*.

Figure 2

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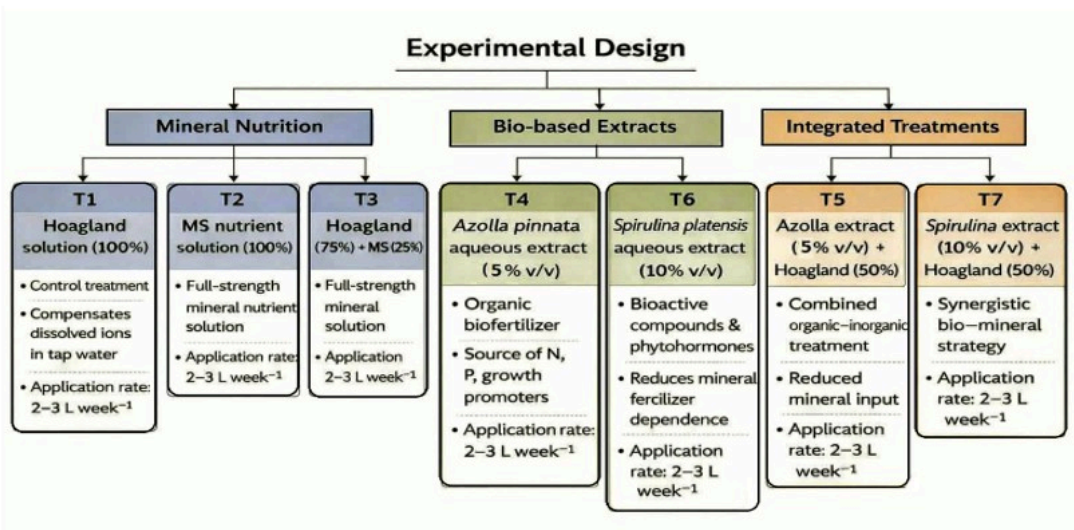

Figure 3. Schematic representation of the experimental setup and composition of mineral, bio-based, and integrated nutrient treatments under the NFT hydroponic system.

Figure 3

See image above for figure legend.