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RESEARCH ARTICLE

Iodine-based nutrient application improves growth, economic yield and agronomic efficiency in tomato

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Abstract

Tomato (*Solanum lycopersicum* L.) is one of the most economical vegetable crop worldwide, often limited by nutrient imbalances and suboptimal management practices. This study evaluated the effect of different iodine sources potassium iodide (KI) and potassium iodate (KIO_3) and application methods (seed priming, soil application and foliar spray) on the growth, phenology and yield of tomato over 2 consecutive years. The experiment comprised 9 treatments laid out in a randomized complete block design (RCBD). The central hypothesis proposed that iodine though not traditionally essential but can enhance photosynthetic performance, flowering efficiency and nutrient-use efficiency. Results revealed that iodine application significantly improved plant height, canopy width and number of branches per plant with the highest values observed under the combined application of KI through seed priming, soil and foliar spray (T8). Foliar applications alone in treatments T4 and T5 also performed effectively and promoted early flowering. Yield parameters including total and marketable yield were significantly enhanced by iodine treatments, with T4 (KI foliar spray) depicting increased total yield by 6.5 % and marketable yield by 7 % over the control. The highest benefit-cost ratio (2.80) was recorded in T4 (KI foliar), indicating superior economic efficiency. The positive responses are attributed to iodine's role in enhancing photosynthetic activity, antioxidant defence and hormonal regulation. While integrated application provided maximum physiological benefits, foliar spray alone emerged as the most practical and cost-effective strategy for field conditions. The study suggested that foliar application of KI at 0.01 % offers a sustainable, cost-effective approach to improve vegetative growth, reproductive efficiency and yield in tomato. This approach offers business potential and precision nutrient management and value-added vegetable production worldwide. Future studies should explore its incorporation with digital nutrient mapping and broader vegetable systems for climate-resilient agriculture.

Keywords: agronomic efficiency; foliar application; iodine; seed priming; sustainable; tomato yield

Introduction

Tomato (*Solanum lycopersicum* L.) is a widely cultivated solanaceous vegetable in the world after potato, valued for its high economic returns, nutritional richness and year-round demand (1). It is a good source of protein, antioxidants vitamins (A and C), minerals and carotenoids (lycopene, beta-cryptoxanthin, zeaxanthin, lutein and beta-carotene) which assist to prevent cancer and degenerative disorders (2). Despite its global significance, tomato production is increasingly constrained by nutrient imbalances, soil degradation and inefficient input management, which limit both yield and quality (3). In this context, nutrient management strategies that improve productivity while enhancing ecological sustainability have gained critical importance in present times (4).

Globally, tomato is cultivated on approximately 5 million hectares, with an annual production exceeding 180 million tonnes and an average productivity of 36 million t ha^{-1}. Tomato is cultivated across all states and union territories of India and holds significant potential in export market. In India, it is cultivated on an area of 0.85 million hectares with production of 21.55 million tonnes and productivity of 25.28 million t ha^{-1} (5).

Among micronutrients, iodine though not traditionally classified as essential for plant growth has recently emerged as a beneficial element, known to influence various physiological, metabolic and reproductive processes in crops (6). Its roles in antioxidant defence, flowering regulation and biomass accumulation has been documented in several horticultural crops, yet systematic studies in tomato remain limited (7). Moreover, iodine's potential to enhance yield quality and resilience under variable environmental conditions presents an untapped opportunity for sustainable intensification (8, 9).

Seed priming represents a promising physiological approach to improve seed performance and early crop establishment. It involves controlled hydration of seeds to initiate pre-germinative metabolic processes without actual germination. This process enhances nutrient uptake, enzyme activation and antioxidant defence mechanisms. This leads to uniform emergence and improved stress resilience (8).

In addition to seed priming, soil and foliar spray offer diverse pathways for plant uptake (10). The soil route supports root absorption and sustained availability, while foliar application provides rapid nutrient assimilation during active vegetative and reproductive phases (11). However, their comparative effects on growth, flowering, yield and resource-use efficiency in tomato are not well established. While combined application strategies may provide comprehensive nutrient access, they are often labour-intensive and may not be economically viable for smallholder farmers (12). Hence, evaluating the agronomic effectiveness and economic efficiency of simplified delivery modes such as foliar sprays is critical for large-scale adoption (13). In addition, any farming technology or input management practice that is to be used on a large scale must indicate not just environmental sustainability, but also financial profitability. It is necessary to create the perspective of an investor and stakeholder into the assessment of the agricultural innovations to guarantee the further implementation of such innovations and funding of the horticultural industry (14).

Despite the increasing recognition of iodine's agronomic value, there is limited research on its synergistic effects when applied through different methods in tomato. Therefore, the present investigation was undertaken to evaluate the impact of different sources [Potassium iodide (KI) and potassium iodate (KIO_3)] and methods (soil application, foliar spray, seed priming and their combinations) of iodine application on tomato growth, early vigour, flowering and yield traits over 2 consecutive years. The study emphasises not only the biological response but also the ecological and economic implications, with the goal of identifying farmer-friendly and sustainable nutrient management strategies for improved tomato productivity.

Materials and Methods

Experiment details

The experiment consisted of 9 treatments involving 2 iodine sources KI and KIO_3 applied through different methods and concentration as shown in Table 1. Seed priming was done by soaking tomato seeds in solution of the respective iodine salt for 12 hr, followed by drying to original moisture content before sowing. Soil applications were given at transplanting by broadcasting and foliar sprays were applied twice at 30 and 45 days after transplanting (DAT). Both KI and KIO_3 were of analytical grade (ACS reagent, ≥ 99.5 % purity; Sigma-Aldrich, USA). The experiment was laid out in a randomized complete block design (RCBD) with 3 replications. The sequential stages of the experimental procedure, from seed sowing to field establishment under iodine treatments, are illustrated in Fig. 1.

Plant material

The study used the tomato cultivar Punjab Ratta developed by the Punjab Agricultural University, Ludhiana, India. This cultivar has determinate growth and dense dark-green foliage, reaches first harvest about 125 DAT. It produces oval, medium-sized, firm and deep-red fruits with an average lycopene content of 8 mg 100 g^1 fresh weight and is suited for processing. Prior to seed priming the seed viability was evaluated following the International Seed Testing Association (ISTA, 2020) protocol. Four replicates of 100 seeds each were incubated on moistened blotter paper at 25 ± 1 °C. Seeds with a radicle length ≥ 2 mm were considered germinated. The mean germination percentage (94.2 ± 1.8 %) showed uniform viability and vigour.

Table 1. Details of iodine treatments with different sources, doses and application methods in tomato

Treatment	Source	Dose	Method of application
T_1	Control		
T_2	KI	1kg $acre^{-1}$	Soil application
T_3	KIO_3	1 kg $acre^{-1}$	Soil application
T_4	KI	0.1 g L^{-1}	Foliar application
T_5	KIO_3	0.1 g L^{-1}	Foliar application
T_6	KI	0.5 mg L^{-1}	Seed priming
T_7	KIO_3	0.5 mg L^{-1}	Seed priming
T_8	$T_2+T_4+T_6$ (KI)	1 kg $acre^{-1}$ + 0.1 g l^{-1} + 0.5 mg L^{-1}	Soil application + Foliar application + Seed priming
T_9	$T_3+T_5+T_7$ (KIO_3)	1 kg $acre^{-1}$ + 0.1 g l^{-1} + 0.5 mg L^{-1}	Soil application + Foliar application + Seed priming

KI is Potassium iodide and KIO_3 is Potassium iodate.

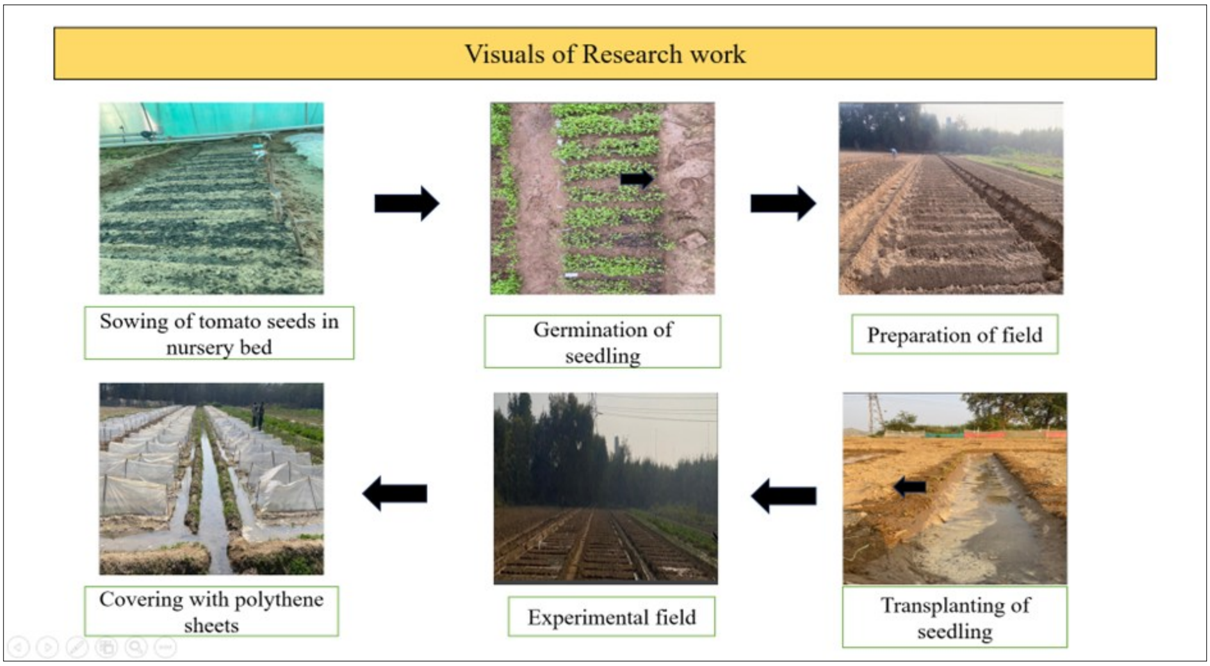


Fig. 1. Stepwise overview of tomato growth and sequential field experimentation.

Observations Recorded

Growth attributes

Plant height (cm): Five plants were chosen at random from each bed and their heights were measured at 30, 60, 90 and 120 DAT. With the use of a measuring tape, it was measured in centimetres from the base of the plant or the soil surface to the highest point. An average value was calculated for each sub-treatment.

Canopy width (cm^2): A representative sample of plants from each plot was chosen to estimate the canopy width. A measuring tape was used to determine the width of the canopy from edge-to-edge perpendicular to the row direction. To account for variability, measurements were made from many plants and an accuracy average was computed.

Days to 50 % flowering: To measure days to 50 % flowering (DFF), the date of sowing was recorded. The plants were monitored daily and when a plant produced flower on half of its nodes, it was said to be in its 50 % flowering stage. The data was recorded when the threshold is reached and calculated the number of days from transplanting.

Number of branches per plant: The number of branches were recorded by first, counting from the main stem, identifying primary branches that emerge directly from it. It included only well-developed branches that show significant growth, excluding minor shoots. The observations were recorded at the maturity of crop.

Total yield (q ha^{-1}): Total yield of tomatoes was measured by harvesting all mature tomatoes from the sampled plots and weighing them accurately at each picking in every replication and further add to get total yield. The sample yield was generalised to the entire field based on the total cultivated area. The total weight was converted from kilograms to quintals (1 quintal = 100 kg).

Marketable yield (q ha^{-1}): Marketable yield was recorded in quintals, by first selecting a representative sample plot within the field. Fruits which were mature, disease-free and undamaged fruits suitable for sale were selected. The total marketable produce from the sample plot was selected and converted the weight into quintals.

Benefit: Cost ratio (B:C ratio)

This was calculated to summarise the economic feasibility of any practice i.e., how much returns were obtained for any rupee spent. B:C was defined as ratio of net returns to the total cost of cultivation. It was calculated by using the formula given below:

$$\text{B:C} = \frac{\text{Net returns (ha}^{-1}\text{)}}{\text{Total cost of cultivation (ha}^{-1}\text{)}}$$

Agronomic efficiency

The agronomic efficiency and partial factor productivity were calculated as per equations (15) as

$$\text{Agronomic efficiency} = \frac{\text{Yield from application of fertilizer - Yield from control plot}}{\text{Amount of fertilizer applied}}$$

$$\text{Partial factor productivity} = \frac{\text{Yield}}{\text{Amount of fertilizer applied}}$$

Statistical analysis

The data were subjected to analysis of variance (ANOVA) using R software. Treatment means were compared using least significant difference (LSD) at 5 % level of significance. Pooled analysis over 2 years was conducted and year-wise data were presented as supplementary material to support observed trends. Economic analysis was performed by computing the benefit-cost ratio based on prevailing market prices and input costs.

Results and Discussion

Plant height at different growth stages

Iodine supplementation showed a significant ($p \leq 0.05$) influence on plant height at all observation stages plant height at all observation stages (Table 2). Among the treatments, T8 (KI applied via seed priming + soil + foliar) consistently recorded the highest plant height throughout the growth period which was statistically at par with T4 (KI foliar) and T5 (KIO_3 foliar).

At 30 DAT, T8 achieved a plant height of 30.58 cm, which was significantly higher than all treatments except T4 (KI foliar spray) and T5 (KIO_3 foliar spray) with values statistically at par. The control (T1) consistently recorded the lowest height (21.86 cm) indicating the beneficial effect of iodine on early vegetative growth. At 60 DAT, T4 (KI foliar spray) resulted in the maximum plant height (51.35 cm), while the control recorded the lowest (47.46 cm) again representing the advantage of foliar applied iodine during active vegetative growth. By 90 DAT, the highest plant height was recorded in T8 (81.57 cm) which was significantly higher than all other treatments. The control (T1) and T2 (KI soil application) exhibited the lowest plant height (72.58 and 72.37 cm) suggesting that sole soil application was less effective than foliar or combined application

Table 2. Effect of different iodine treatments and application methods on plant height at different intervals

Sl. No.	Treatment	Method of application	Plant height (cm)			
			30 DAT	60 DAT	90 DAT	120 DAT
T_1	Control		21.86 ± 1.01^{e}	47.46 ± 0.21^{a}	72.58 ± 0.86^{d}	87.54 ± 1.13^{c}
T_2	KI	Soil application	23.66 ± 0.70^{de}	47.67 ± 1.45^{a}	72.37 ± 0.57^{d}	90.45 ± 0.98^{c}
T_3	KIO_3	Soil application	24.38 ± 0.99^{de}	48.98 ± 1.70^{a}	73.74 ± 0.25^{cd}	90.93 ± 2.07^{c}
T_4	KI	Foliar application	29.96 ± 0.70^{ab}	51.35 ± 1.96^{a}	76.50 ± 1.12^{bc}	104.20 ± 1.03^{ab}
T_5	KIO_3	Foliar application	30.11 ± 0.50^{ab}	50.95 ± 1.07^{a}	75.22 ± 2.11^{bcd}	104.18 ± 2.31^{ab}
T_6	KI	Seed priming	25.84 ± 0.75^{cd}	48.45 ± 1.62^{a}	74.92 ± 0.93^{bcd}	88.43 ± 0.64^{c}
T_7	KIO_3	Seed priming	25.29 ± 0.64^{cd}	47.82 ± 1.63^{a}	74.00 ± 0.38^{cd}	88.22 ± 2.28^{c}
T_8	KI	SP+SA+FA	30.58 ± 1.09^{a}	49.91 ± 2.73^{a}	81.57 ± 1.35^{a}	105.13 ± 2.56^{a}
T_9	KIO_3	SP+SA+FA	27.77 ± 1.31^{bc}	48.94 ± 1.35^{a}	77.43 ± 1.21^{b}	99.27 ± 2.39^{b}
	LSD ($p \leq 0.05$)		2.72	4.46	3.18	8.04
	CV (%)		3.2	5.26	2.44	3.22

Values are presented as means ± SE. Bars labeled with different letters represent significant differences, determined by Duncan's multiple range test ($p \leq 0.05$). DAT: Days after transplanting; SA: Soil application; SP: Seed priming; FA: Foliar application.

methods. At 120 DAT, T8 again showed highest response with 105.13 cm, statistically at par only with T4 (104.20 cm) and T5 (104.18 cm). The control (T1) had the minimum plant height at this stage (87.54 cm).

Although year-wise variation existed, the general trend of treatment performance remained similar, as shown in the Supplementary Table 1. These findings emphasise that foliar and combined applications of iodine, particularly through KI, promoted robust vegetative growth and plant stature. The enhanced response under T8 could be attributed to improved nutrient uptake and translocation, which are known to be more efficient with foliar and priming interventions (16). The consistent superiority of KI-based treatments indicates iodine's physiological role in enhancing cell elongation, meristem activity and photosynthetic efficiency (8). Foliar and combined applications likely facilitated more effective nutrient absorption and translocation, resulting in greater vegetative vigour. Similar findings were reported by previous researchers (6, 11).

Canopy width (cm^2)

Canopy width differed significantly among iodine treatments (Table 3). The widest canopy was recorded under T8 (KI via seed priming + soil + foliar application) at 45.63 cm^2 which was significantly higher than T2, T3, T7 and the control (T1). The narrowest canopy was observed in the control (36.52 cm^2). The broader canopy under T8 suggests improved shoot development, likely due to enhanced nutrient availability and uptake efficiency. This trait is agronomically desirable, as it improves light interception and biomass accumulation (17). The increase in canopy spread under iodine application suggests enhanced shoot development and leaf expansion, improving light interception and photosynthetic capacity. These results align with previous studies, that demonstrated improved canopy architecture following iodine biofortification (9). Despite minor year-to-year variation (Supplementary Table 2) the trend remained consistent confirming the benefit of integrated iodine application for canopy development and overall vigour.

Number of branches per plant

Although the differences among treatments were not statistically significant in iodine treated plants (Table 3). However, T3, T5 and T8 recorded the highest number of branches (12.17), while the lowest was in the control (7.33). The trend consistent across both years indicates that iodine particularly when applied in combined or foliar spray alone may support greater shoot proliferation due to improved hormonal activity (18). The trend indicates iodine's role in stimulating cytokinin-mediated lateral bud activation, promoting more prolific shoot formation even without large statistical separation. Similar hormonal responses were noted in previous studies (19, 11).

Days to 50 % flowering

The time to 50 % flowering varied significantly among treatments (Table 3). While T8 (KI via combined application) recorded the earliest flowering (69.86 days), T4 (KI foliar spray) also resulted in early flowering and was statistically at par with other. Given the ease and cost-effectiveness of foliar application, T4 represents a more practical option for achieving early flowering under field conditions. This trend was consistent over both years (Supplementary Table 2). Early flowering is advantageous under stress-prone or short season conditions, beneficial for improving fruit set and yield stability. The advancement in flowering under iodine treatments reflects its role in hormonal regulation (gibberellins and cytokinin) and antioxidant activation, facilitating earlier reproductive transition (20). Comparable effects of iodine on accelerated flowering were reported previously (8). The enhanced phenology under iodine treatments implies that iodine may act as a bio stimulant, reducing the duration to reproductive maturity and improving synchronisation of flowering and fruit set traits (11).

Total and marketable yield (q ha^{-1})

Iodine application showed significantly affect ($p \leq 0.05$) on both total and marketable yield in tomato (Table 4). The maximum total yield was recorded under T8 (KI via seed priming + soil + foliar) with 568.79 q ha^{-1}, followed closely by T9 (KIO_3 combined), T4 (KI foliar) and T5 (KIO_3 foliar). These treatments were statistically at par with other. The lowest yield was recorded in the control (T1) at 527.71 q ha^{-1}. The year-wise data as shown in Fig. 2 supported the consistency of this trend. A similar pattern was observed for marketable yield. T8 again recorded the highest marketable yield (479.25 q ha^{-1}), followed by T9, T4, T5, T6 and T7 all of which were statistically at par with other. Data regarding 2 consecutive years was shown in Supplementary Table 3. The significant increase in both total yield under foliar and combined iodine applications may result from a cumulative effect of enhanced source-sink balance, improved fruit set percentage and greater assimilate partitioning toward reproductive organs (21, 22). Iodine likely supports efficient vascular transport, sugar accumulation and hormonal signalling. These all factors are crucial for fruit development and seed filling (23).

Benefit-cost ratio

Economic analysis showed a significant improvement in profitability under iodine treatments (Table 4). The T4 (KI foliar application) had the highest B:C ratio (2.80), followed by T5 (KIO_3 foliar) at 2.78, both of

Table 3. Influence of iodine treatments and application methods on canopy architecture and phenological traits in tomato

Sl. No.	Treatment	Method of application	Canopy width (cm^2)	Number of branches $plant^{-1}$	Days to 50% flowering
T_1	Control		36.52 ± 0.89^{d}	7.33 ± 0.44^{b}	80.14 ± 1.33^{a}
T_2	KI	Soil application	39.78 ± 0.70^{cd}	10.50 ± 1.15^{ab}	75.70 ± 1.56^{ab}
T_3	KIO_3	Soil application	39.96 ± 0.62^{bcd}	12.17 ± 1.42^{a}	75.54 ± 1.44^{ab}
T_4	KI	Foliar application	45.31 ± 3.91^{ab}	11.50 ± 0.29^{a}	70.43 ± 0.72^{cd}
T_5	KIO_3	Foliar application	44.84 ± 0.41^{abc}	12.17 ± 0.73^{a}	70.80 ± 2.24^{cd}
T_6	KI	Seed priming	40.52 ± 1.54^{abcd}	11.00 ± 0.76^{a}	74.43 ± 1.75^{bcd}
T_7	KIO_3	Seed priming	40.16 ± 1.88^{bcd}	11.00 ± 0.76^{a}	75.05 ± 1.35^{bcd}
T_8	KI	SP+SA+FA	45.63 ± 1.93^{a}	12.17 ± 1.42^{a}	69.86 ± 1.90^{d}
T_9	KIO_3	SP+SA+FA	42.61 ± 3.19^{abc}	11.17 ± 1.59^{ab}	73.03 ± 0.90^{bcd}
	LSD ($p \leq 0.05$)		5.44	3.16	4.67
	CV (%)		6.18	11.92	3.65

Values are presented as means ± SE. Bars labelled with different letters represent significant differences, determined by Duncan's multiple range test ($p \leq 0.05$). SA: Soil application; SP: Seed priming; FA: Foliar application.

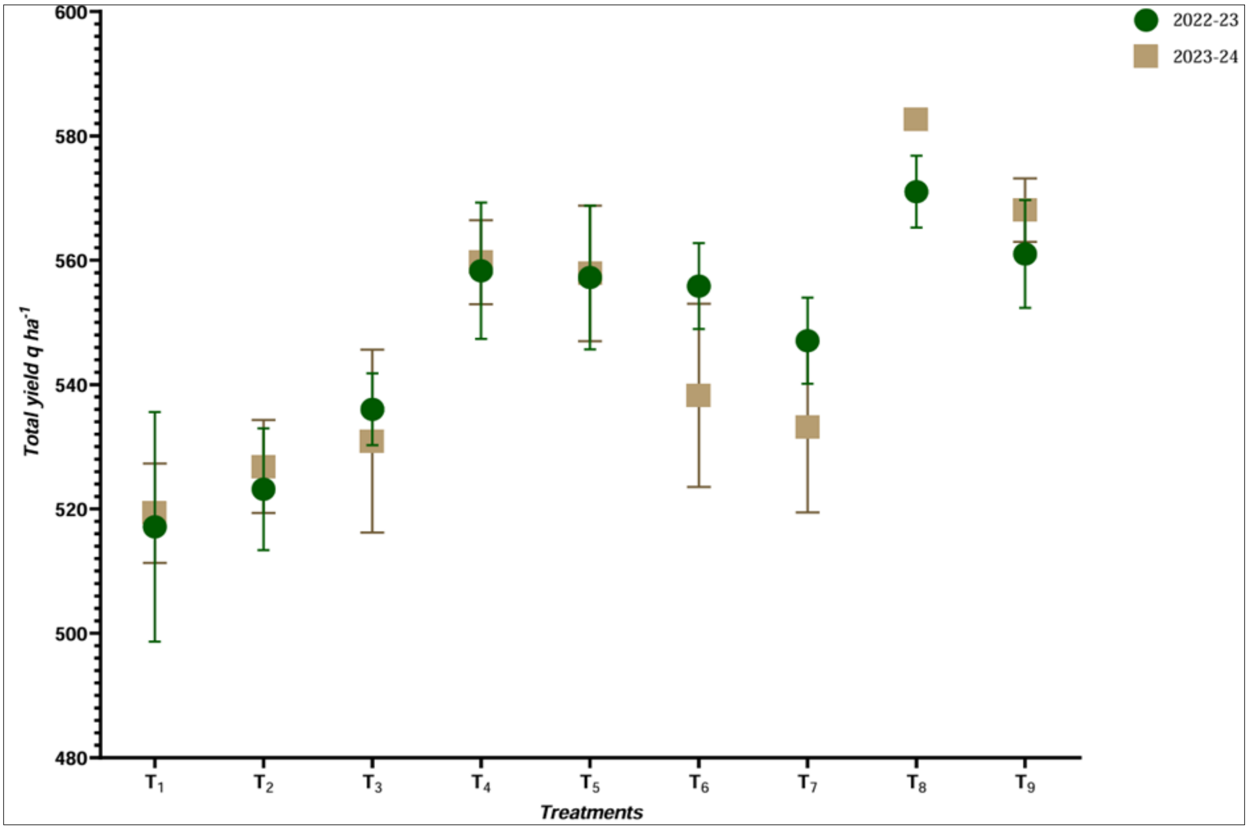


Fig. 2. Effect of different treatments on total yield of tomato across 2 growing seasons.

which outperformed the combined application (T8) in terms of economic return. The control (T1) had the lowest B:C ratio of 2.44 as represented in Table 4. Although combined applications (e.g., T8) provided the maximum agronomic response, they involve multiple input stages seed priming, soil incorporation and foliar spraying which may not be feasible for many farmers due to labour intensity and input costs. In contrast, foliar application alone emerged as the most practical and cost-effective strategy, offering a strong balance between yield gain and profitability (24). Furthermore, new computational technologies including digital twin simulations currently provide the opportunity to model a plant production system in a virtual environment and predict its techno-economic effectiveness and sustainability over the long term in different situations (25, 26).

Agronomic efficiency

Both agronomic efficiency (AE) and partial factor productivity (PFP) varied widely across treatments (Table 4). The data shown in Table 4 clearly indicate that foliar applications of KI (T4) and KIO_3 (T5) were the most efficient and practical treatments showing high agronomic efficiency of 500.32 and 477.28 kg fruit ha^{-1} g^{-1} fertiliser, respectively. These treatments also confirmed superior partial factor productivity (PFP) emphasising the maximum yield obtained per unit of fertiliser applied due to the minimal input required in foliar spray and efficient nutrient uptake through leaves. Although, seed priming T6 and T7 recorded exceptionally high AE and PFP values. These are attributed to the extremely small fertiliser doses used and may not be practically scalable or reliable for direct field-level recommendations. Combined treatments of iodine T8 and T9 showed improved yield but moderately lower efficiency when compared to foliar application alone, due to higher total input requirement. Therefore, considering ease of application, economic viability and farmer acceptability foliar application alone appears as the most effective strategy (19). Therefore, foliar application provided a statistically superior and practically efficient nutrient-use response consistent with earlier reports (27).

Table 4. Effect of iodine treatments on yield performance and economic return in tomato

Sl. No.	Treatment	Method of application	Total yield (qha^{-1})	Marketable yield (qha^{-1})	Agronomic efficiency (kg fruit ha^{-1} g^{-1} fertiliser)	Partial factor productivity (kg fruit g^{-1} fertiliser applied)	B:C ratio
T_1	Control		527.71 ± 2.55^{e}	435.05 ± 2.24^{d}	-	-	2.44
T_2	KI	Soil application	525.00 ± 2.23^{e}	456.52 ± 1.86^{c}	0.12	21.41	2.45
T_3	KIO_3	Soil application	533.46 ± 7.07^{de}	461.43 ± 6.15^{bc}	0.56	21.58	2.52
T_4	KI	Foliar application	558.98 ± 6.68^{ab}	475.12 ± 5.70^{ab}	500.32	89.43	2.8
T_5	KIO_3	Foliar application	557.53 ± 6.75^{abc}	473.90 ± 5.74^{ab}	477.28	87.20	2.78
T_6	KI	Seed priming	547.05 ± 5.11^{bcd}	470.64 ± 4.24^{abc}	8909.52	5.11×10^{5}	2.55
T_7	KIO_3	Seed priming	540.13 ± 9.43^{cde}	469.98 ± 8.16^{abc}	1386.17	3.03×10^{5}	2.48
T_8	KI	SP+SA+FA	568.79 ± 3.51^{a}	479.25 ± 3.08^{a}	4.08	22.96	2.75
T_9	KIO_3	SP+SA+FA	564.54 ± 3.14^{ab}	477.09 ± 2.59^{a}	3.66	22.97	2.71
	LSD ($p \le 0.05$)		17.83	15.29			
	CV (%)		4.59	4.29			

Values are presented as means ± SE. Bars labelled with different letters represent significant differences, determined by Duncan's multiple range test ($p \le 0.05$). SA: Soil application; SP: Seed priming; FA: Foliar application.

Correlation matrix

The correlation analysis revealed strong positive relationships among plant height recorded at different days after transplanting (30, 60, 90 and 120 DAT) indicating consistent vegetative growth trends. Plant height showed significant positive correlations with total yield and marketable yield showed in Fig. 3. Further suggesting that plants with more height generally resulted in better yield performance. Canopy width also exhibited a moderate to strong positive association with yield components, whereas DFF showed a significant negative correlation with most parameters. It implying that early flowering contributed positively to yield aspects. Effect of different treatments on various traits is also depicted through colour gradient in heat map (Fig. 4).

Principal component analysis

The principal component analysis (PCA) results further supported these findings, where the scree plot showed that the first 2 principal components accounted for over 98 % of the total variation, with PC1 alone explaining 91.4 %. The biplot clearly grouped traits like plant height, canopy width, total yield and marketable yield along PC1, confirming their major contribution to the observed variability among treatments as shown in Fig. 5. In contrast, DFF and number of branches per plant (NBPP) aligned negatively along PC2 and PC1, respectively, indicating contrasting effects. This multivariate approach effectively distinguished the most influential traits contributing to yield enhancement under the studied treatments.

Practical implications

The results emphasise the role of iodine as a low-dose, high-impact input that can enhance crop performance without placing additional stress on soil health or requiring excessive fertiliser use. Foliar application aligns with sustainable intensification principles contributing precision nutrient distribution, minimal runoff loss and cost-efficiency (27). Given the labour and input burden associated with combined application methods [Seed priming (SP)+ Soil application (SA)+ Foliar application (FA)], promoting foliar spray of KI emerges as a practical suggestion for wider on-farm adoption. It balances biological efficacy with operational simplicity, making it highly suitable for resource-limited and smallholder contexts. In line with current advances in sustainable nutrient management new technologies in crop production include coir pith-produced silica nanoparticle-based nutrient delivery system synthesised through the acidic sol-gel technique and biochar-mediated regulation of the denitrifies activity and thus minimising N_2O emissions are redefining the efficiency and economic sustainability of fertiliser in agriculture (28). Recent technology operating under different economies of farming, now predictive evaluation on the techno-economic and sustainability performance of such nutrient management innovations is achievable by emerging artificial intelligence (AI) and digital twin systems (29, 30).

Conclusion

This research confirms the central hypothesis that iodine, though not conventionally essential, is used as a bio-stimulant which increases physiological performance, yield and the efficiency of nutrient use in tomato. The findings collectively indicate that highest performance observed under combined application of KI through seed priming, soil and foliar spray (T8). However, the foliar application of KI alone (T4) produced comparable agronomic benefits and achieved the highest benefit-cost ratio, making it a more practical and economically viable strategy for tomato growers. Under the specific agro-climatic and management conditions of this study, foliar spraying of potassium iodide (KI) at 0.1 g L^{-1} concentration can be considered as a promising and sustainable approach to enhance early vigour, flowering efficiency and yield in tomato under field conditions while, ensuring better resource-use efficiency and supporting ecological intensification. Nonetheless, multi-season and multi-location trials are recommended to validate these findings across diverse environments and to assess the long-term agronomic and environmental implications of iodine supplementation in vegetable production systems.

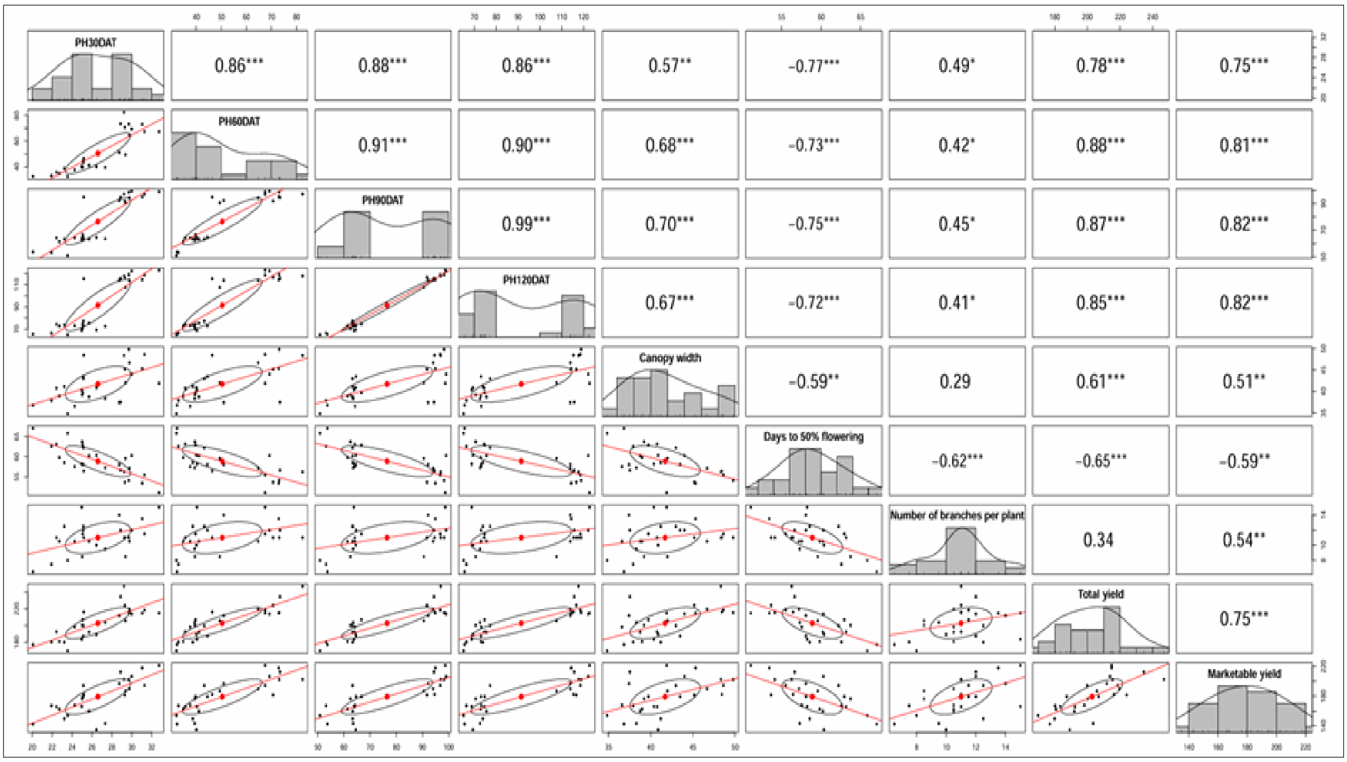


Fig. 3. Pearson correlation matrix of growth, yield and phenological traits in tomato under different treatment.

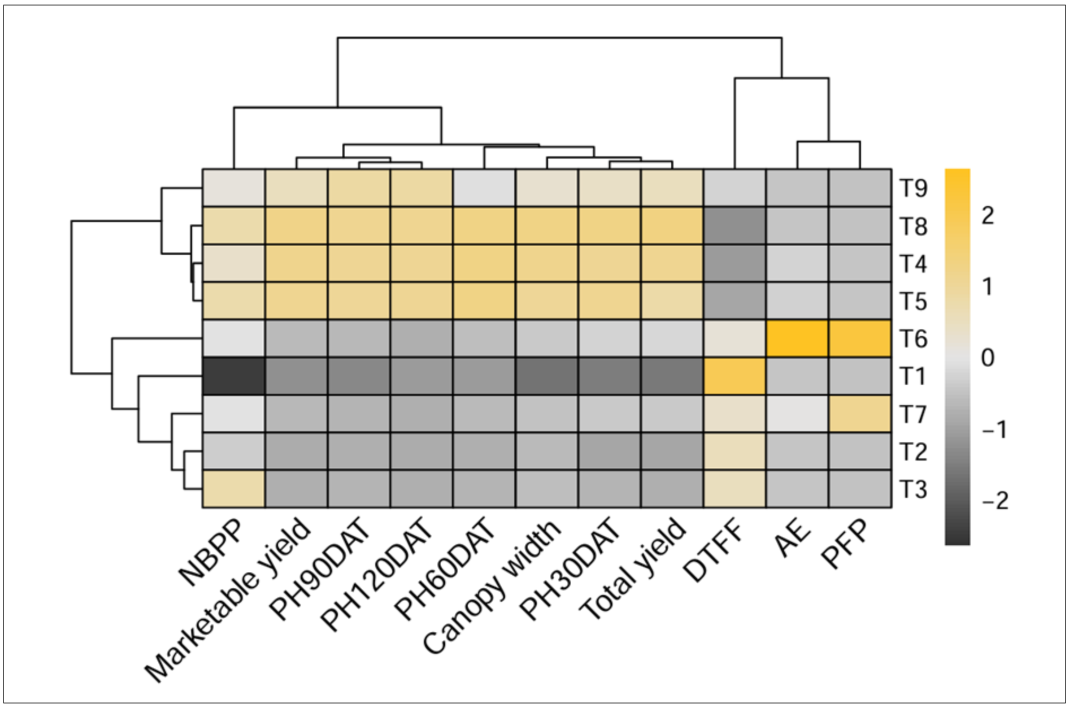
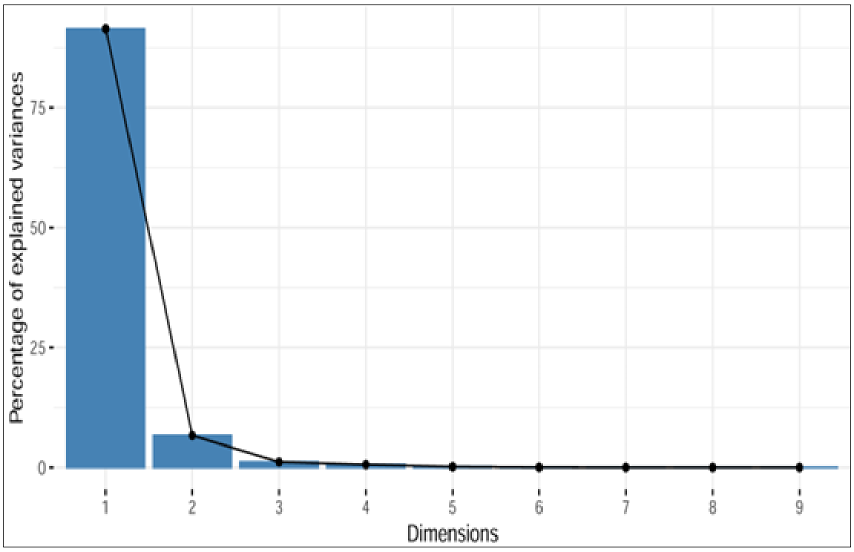
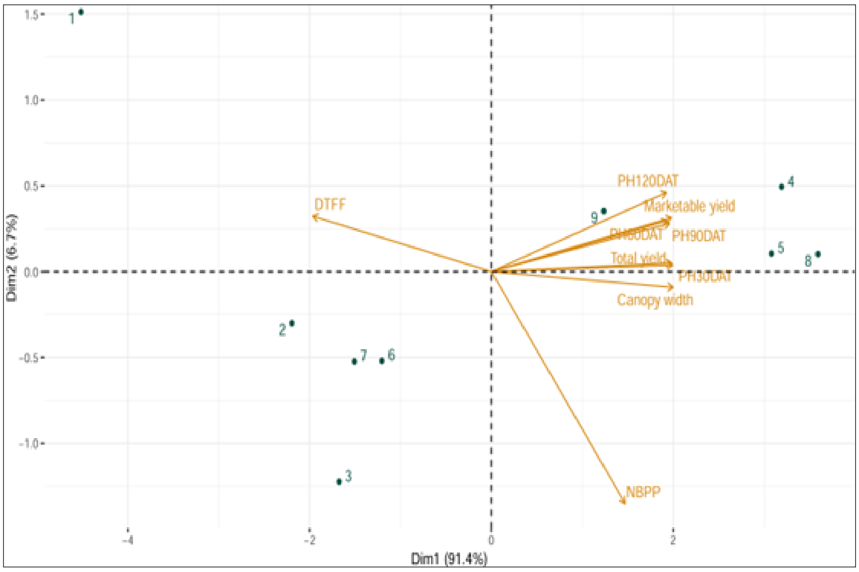


Fig. 4. Heatmap of growth and yield traits in tomato across different treatments.



Scree plot



PCA biplot

Fig. 5. Principal component analysis of growth and yield attributes in tomato: Scree plot and biplot.

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Authors' contributions

B, DT and KS conceptualised and designed the study. B conducted the investigation, performed data curation and prepared the original draft. MT and DT contributed to formal analysis, visualisation and assisted in data interpretation. JS & SKJ supervised the research, provided project oversight and critically reviewed and edited the manuscript. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflict of interest to declare.

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References

1. Ahmed R, Abd Samad MY, Uddin MK, Quddus MA, Motalib Hossain MA. Recent trends in the foliar spraying of zinc nutrient and zinc oxide nanoparticles in tomato production. Agronomy. 2021;11. https://doi.org/10.3390/agronomy11102074.
2. Wang C, Li M, Duan X, Abu-Izneid T, Rauf A, Khan Z, et al. Phytochemical and nutritional profiling of tomatoes; impact of processing on bioavailability-a comprehensive review. Food Rev Int. 2023;39:5986–6010.https://doi.org/10.1080/87559129.2022.2097692
3. Yang J, Mattoo AK, Liu Y, Zvomuya F, He H. Trade-offs of organic and organic-inorganic fertiliser combinations in tomato quality and yield: A global meta-analysis (1992–2021). Euro J Agron. 2023;151:126985. https://doi.org/10.1016/j.eja.2023.126985.
4. Al-Shammary AAG, Al-Shihmani LSS, Fernández-Gálvez J, Caballero-Calvo A. Optimizing sustainable agriculture: A comprehensive review of agronomic practices and their impacts on soil attributes. J Environ Manage. 2024;364:121487. https://doi.org/10.1016/j.jenvman.2024.121487.
5. Indiatstat. Datanet India Pvt. Ltd. Socio-economic information domain. ITeS company; 2000. https://www.indiastat.com
6. Kiferle C, Martinelli M, Salzano AM, Gonzali S, Beltrami S, Salvadori PA, et al. Evidences for a nutritional role of iodine in plants. Front Plant Sci. 2021;12. https://doi.org/10.3389/fpls.2021.616868.
7. Sacco A, Raiola A, Calafiore R, Barone A, Rigano MM. New insights in the control of antioxidants accumulation in tomato by transcriptomic analyses of genotypes exhibiting contrasting levels of fruit metabolites. BMC Genomics. 2019;20:43. https://doi.org/10.1186/s12864-019-5428-4.
8. Medrano-Macías J, Leija-Martínez P, González-Morales S, Juárez-Maldonado A, Benavides-Mendoza A. Use of Iodine to Biofortify and Promote Growth and Stress Tolerance in Crops. Front Plant Sci. 2016;7. https://doi.org/10.3389/fpls.2016.01146.
9. Zhang Y, Cao H, Wang M, Zou Z, Zhou P, Wang X, et al. A review of iodine in plants with biofortification: Uptake, accumulation, transportation, function and toxicity. Sci Total Environ. 2023;878:163203. https://doi.org/10.1016/j.scitotenv.2023.163203.
10. Lawson PG, Daum D, Czauderna R, Meuser H, Härtling JW. Soil versus foliar iodine fertilization as a biofortification strategy for field-grown vegetables. Front Plant Sci. 2015;6. https://doi.org/10.3389/fpls.2015.00450.
11. Riyazuddin R, Singh K, Iqbal N, Nisha N, Rani A, Kumar M, et al. Iodine: an emerging biostimulant of growth and stress responses in plants. Plant Soil. 2023;486:119–33. https://doi.org/10.1007/s11104-022-05750-5
12. Collins EJ, Bowyer C, Tsouza A, Chopra M. Tomatoes: An extensive review of the associated health impacts of tomatoes and factors that can affect their cultivation. Biology (Basel). 2022;11:239. https://doi.org/10.3390/biology11020239
13. Karunathilake EMBM, Le AT, Heo S, Chung YS, Mansoor S. The path to smart farming: innovations and opportunities in precision agriculture. Agric. 2023;13:1593. https://doi.org/10.3390/agriculture13081593
14. Ajayi OC. User acceptability of sustainable soil fertility technologies: Lessons from farmers' knowledge, attitude and practice in southern Africa. J Sustain Agric. 2007;30(3):21–40. https://doi.org/10.1300/J064v30n03_04
15. Dobermann A. Nutrient use efficiency–measurement and management. In: IFA international workshop on fertiliser best management practices, Brussels, Belgium; 2007. p.1–28.
16. Moradi L, Siosemardeh A. Combination of seed priming and nutrient foliar application improved physiological attributes, grain yield and biofortification of rainfed wheat. Front Plant Sci. 2023;14:1287677. https://doi.org/10.3389/fpls.2023.1287677
17. Sinclair TR, Vadez V. Physiological traits for crop yield improvement in low N and P environments. Plant and Soil. 2002;245(1):1–5. https://doi.org/10.1023/A:1020624015351
18. Ikram NA, Ghaffar A, Khan AA, Nawaz F, Hussain A. Foliar iodine application: A strategy for tomato biofortification and yield optimization. J Plant Nutr. 2025;48(3):540–56. https://doi.org/10.1080/01904167.2024.2407483
19. Li X, Cao X, Li J, Xu J, Ma W, Wang H, et al. Effects of high potassium iodate intake on iodine metabolism and antioxidant capacity in rats. J Trace Elem Med Bio. 2020;62:126575. https://doi.org/10.1016/j.jtemb.2020.126575.
20. Castro-Camba R, Sánchez C, Vidal N, Vielba JM. Plant development and crop yield: The role of gibberellins. Plants. 2022;11(19):2650. https://doi.org/10.3390/plants11192650
21. Smith MR, Rao IM, Merchant A. Source-sink relationships in crop plants and their influence on yield development and nutritional quality. Front Plant Sci. 2018;9. https://doi.org/10.3389/fpls.2018.01889
22. Julius BT, Leach KA, Tran TM, Mertz RA, Braun DM. Sugar transporters in plants: New insights and discoveries. Plant Cell Physiol. 2017;58:1442–60. https://doi.org/10.1093/pcp/pcx090.
23. Allahverdian M, Rahmani F. Epibrassinolide seed priming alleviates alkaline stress by enhancing antioxidant defense in dragonhead plants. Sci Reports. 2025. https://doi.org/10.1038/s41598-025-30763-2
24. Alim MA, Hossain SI, Ditta A, Hasan MK, Islam MR, Hafeez AG, et al. Comparative efficacy of foliar plus soil application of urea versus conventional application methods for enhanced growth, yield, agronomic efficiency and economic benefits in rice. ACS Omega. 2023;8(39):35845–55. https://doi.org/10.1021/acsomega.3c03483
25. Stefko R, Frajtova-Michalikova K, Strakova J, Novak A. Digital twin-based virtual factory and cyber-physical production systems, collaborative autonomous robotic and networked manufacturing technologies and enterprise and business intelligence algorithms for industrial metaverse. Equilibrium. J Econ Policy. 2025;20(1):389–425. https://doi.org/10.24136/eq.3557
26. Chatterjee S, Kliestik T, Rowland Z, Bugaj M. Immersive collaborative business process and extended reality-driven industrial metaverse technologies for economic value co-creation in 3D digital twin factories. Oeconomia Copernicana. 2025;16(1).

https://doi.org/10.24136/oc.3596

27. Nakachew K, Yigermal H, Assefa F, Gelaye Y, Ali S. Review on enhancing the efficiency of fertiliser utilization: Strategies for optimal nutrient management. Open Agric. 2024;9. https://doi.org/10.1515/opag-2022-0356
28. Minofar B, Milčić N, Maroušek J, Gavurová B, Maroušková A. Understanding the molecular mechanisms of interactions between biochar and denitrifiers in N_2O emissions reduction: Pathway to more economical and sustainable fertilisers. Soil Tillage Res. 2025;248:106405. https://doi.org/10.1016/j.still.2024.106405
29. Kliestik T, Kral P, Bugaj M, Durana P. Generative artificial intelligence of things systems, multisensory immersive extended reality technologies and algorithmic big data simulation and modelling tools in digital twin industrial metaverse. Equilibrium. 2024;19(2). https://doi.org/10.24136/eq.3108
30. Zvarikova K, Gajanova L, Horak J. Exploring CSR performance as a proxy for competitive advantage across sectors in the Central European countries. Oeconomia Copernicana. 2024;15(3). https://doi.org/10.24136/oc.3247

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