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FOLIAR APPLICATION OF HOTSPOT BIO-STIMULANT IMPROVES VEGETATIVE GROWTH, FRUIT YIELD, QUALITY, AND NUTRIENT UPTAKE IN TOMATO (SOLANUM LYCOPERSICUM L.) UNDER EASTERN DRY ZONE CONDITIONS OF KARNATAKA, INDIA

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ABSTRACT
Tomato (Solanum lycopersicum L.) is a globally vital horticultural crop, yet its productivity under South Indian conditions is often constrained by sub-optimal nutrient availability and canopy development. The present investigation evaluated the dose-response efficacy of HOTSPOT, a proprietary foliar bio-stimulant, at four concentrations (2, 2.5, 3, and 5 ml L^{-1}) on growth, yield, fruit quality, and N-P-K uptake in tomato during Rabi 2024-25 at the University of Agricultural Sciences (UAS), GKVK, Bangalore. A Randomized Complete Block Design (RCBD) with five treatments replicated four times was employed. Foliar application of HOTSPOT significantly enhanced plant height (up to 128.81 cm), branching (15.47 per plant), leaf area, dry matter accumulation, and fruit yield parameters relative to the untreated control. T5 (5 ml L^{-1}) recorded the highest fruit yield (252.98 q ha^{-1}; +28.97% over control) with superior fruit weight (110.74 g), fruit diameter (6.80 cm), and lycopene content (3.96 mg 100 g^{-1}). Nutrient uptake of N (98.53), P (49.93), and K (112.76 kg ha^{-1}) was also significantly higher under T5. No phytotoxicity was observed at any dose. Economically, T4 (3 ml L^{-1}) delivered the highest cost-benefit ratio (1:6.76), making it the recommended dose for smallholder tomato producers. These results demonstrate that HOTSPOT bio-stimulant at 3 ml L^{-1} represents the optimal agronomic and economic rate for tomato production in the Eastern Dry Zone of Karnataka..

KEYWORDS: bio-stimulant; HOTSPOT; Solanum lycopersicum; foliar spray; fruit quality; lycopene; nutrient uptake; cost-benefit

INTRODUCTION
Tomato (Solanum lycopersicum L., family Solanaceae) is the second most important vegetable crop in the world in terms of production volume, with global output exceeding 186 million tonnes across 5.0 million hectares (FAOSTAT, 2023). In India, tomato ranks among the top three vegetable crops and is widely cultivated in diverse agroclimatic regions, including the Eastern Dry Zone of Karnataka, where it forms a key component of the Rabi cropping system. Despite its commercial importance, average productivity in India (approximately 240 q ha^{-1}) remains significantly below the global potential of 500-600 q ha^{-1}, a gap attributable to inadequate canopy management, soil fertility constraints, and sub-optimal use of yield-promoting inputs.

In recent years, plant bio-stimulants have emerged as a sustainable strategy to bridge the yield gap without proportionally increasing the ecological footprint of crop production. Bio-stimulants are defined as "substances or microorganisms that, when applied to plants or the rhizosphere, stimulate natural processes to enhance nutrient uptake, nutrient use efficiency, tolerance to abiotic stresses, and crop quality" (du Jardin, 2015). Unlike conventional fertilizers, bio-stimulants act on plant metabolism through the activation of enzymatic systems, improved phytohormone signalling, and enhanced root architecture (Nardi et al., 2016). Their foliar application is particularly advantageous in tomato, where it bypasses soil-mediated nutrient fixation, ensures rapid absorption via stomata and the cuticle, and can be precisely timed to coincide with critical developmental phases (Colla et al., 2015).

HOTSPOT is a proprietary poly-nutrient bio-stimulant formulation manufactured by Meenakshi Agro Chemicals, Hyderabad, India. While bio-stimulant effects on tomato have been documented for humic acid (Nardi et al., 2016), seaweed extracts (Battacharyya et al., 2015), and protein hydrolysates (Colla et al., 2015), dose-response data for composite commercial formulations specific to South Indian edaphoclimatic conditions are scarce. Establishing such evidence is critical for product registration under the Fertiliser (Inorganic, Organic or Mixed) (Control) Order, 1985, and for science-based extension advisory.

The present study was therefore designed to: (i) quantify the effect of escalating HOTSPOT concentrations on vegetative growth and dry matter accumulation in tomato; (ii) assess yield response in terms of fruit weight, fruit number, and total fruit yield per hectare; (iii) evaluate fruit nutritional quality (TSS, vitamin C, lycopene); (iv) determine N, P, and K uptake as indicators of nutrient use efficiency; and (v) identify the economically optimal application dose via cost-benefit analysis. We hypothesized that HOTSPOT application would significantly improve all assessed parameters in a dose-dependent manner, and that an intermediate dose would provide the most favorable economic outcome.

2. MATERIALS AND METHODS

2.1 Experimental Site

The field experiment was conducted during Rabi season (October 2024 - February 2025) at the AICRP on Sunflower, Zonal Agricultural Research Institute (ZARS), Gandhi Krishi Vigyan Kendra (GKVK), University of Agricultural Sciences (UAS), Bangalore. The site is located at 13°05′ N latitude, 77°34′ E longitude, at 924 m above mean sea level, within Agroclimatic Zone V (Eastern Dry Zone) of Karnataka.

2.2 Soil Characteristics

The experimental soil was red sandy loam (Alfisol order) with: coarse sand 53.4%, fine sand 14.8%, silt 16.6%, clay 15.2%; pH 5.89 (acidic); electrical conductivity 0.35 dS m^{-1}; organic carbon 0.48%. Pre-sowing soil analysis revealed low available N (239.04 kg ha^{-1}), medium available P (25.13 kg ha^{-1}), and medium available K (248.31 kg ha^{-1}). These represent typical Alfisol fertility constraints under rainfed tomato production.

2.3 Climatic Conditions during the Cropping Season

Total seasonal rainfall during October 2024 to February 2025 was 485.6 mm, primarily received in October-November. Mean maximum temperature ranged from 25.2 to 29.8 °C and mean minimum temperature from 13.5 to 16.9 °C across the season. Maximum relative humidity ranged from 90 to 91% and minimum relative humidity from 42 to 90%, providing a moderately warm and humid environment favorable for tomato growth.

2.4 Experimental Design and Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with five treatments and four replications (20 plots total). Each plot measured 5.0 m × 5.0 m (25 m^2), with 0.5 m buffer bunds between adjacent plots and 1.0 m alleyways between replications. Thirty-day-old tomato seedlings were transplanted to the main field at a spacing of 50 cm × 50 cm (40,000 plants ha^{-1}). The five treatments evaluated were:

T1: Untreated control (no bio-stimulant, farmers' practice)
T2: HOTSPOT foliar spray @ 2 ml L^{-1} of water
T3: HOTSPOT foliar spray @ 2.5 ml L^{-1} of water
T4: HOTSPOT foliar spray @ 3 ml L^{-1} of water
T5: HOTSPOT foliar spray @ 5 ml L^{-1} of water

Foliar sprays were applied four times: at 30 DAT (active vegetative stage), 45 DAT (pre-flowering), 60 DAT (fruit setting), and 75 DAT (fruit colour change), using a hand-operated knapsack sprayer with a flat-fan nozzle. Recommended FYM was incorporated two weeks before transplanting, and NPK fertilizers (DAP and muriate of potash) were applied as per crop requirements. Late blight disease (Phytophthora infestans Mont. de Bary) was managed uniformly across all plots using Ametoctradin 27% + Dimethomorph 20.27% SC @ 2 ml L^{-1}, ensuring that phytosanitary status did not confound treatment comparisons.

2.5 Data Collection

Five randomly tagged plants per plot were measured at 30, 60, 90 DAT, and at harvest for plant height (cm), number of primary branches $plant^{-1}$, stem diameter (cm), number of green leaves $plant^{-1}$, leaf area (cm^2 $plant^{-1}$, by leaf area meter), and LAI. Total dry weight (g $plant^{-1}$) was determined by oven-drying all plant parts at 65 °C to constant weight. Fruits were harvested four times at five-day intervals; fruit weight (g), diameter (cm), volume (cc), number per plant, and yield (kg $plant^{-1}$ and q ha^{-1}) were recorded from five sampled plants per plot. TSS (°Brix) was measured by hand-held refractometer; vitamin C by titrimetry (AOAC, 2000); lycopene by hexane extraction and spectrophotometry at 503 nm (Nagata and Yamashita, 1992). Nutrient uptake (kg ha^{-1}) was calculated from di-acid digested tissue analysed for N (micro-Kjeldahl), P (colorimetry, 660 nm), and K (flame photometry) (Jackson, 1973). Phytotoxicity was scored on a 0-10 scale for eight symptom parameters at 3, 7, 10, and 14 days after each application.

2.6 Statistical Analysis

All data were subjected to Analysis of Variance (ANOVA) for RCBD (Cochran and Cox, 1957). Treatment differences were declared significant at $P \leq 0.05$. Standard error of mean (S.Em±) and critical difference (CD at 5%) were computed for each variable. Statistical computations were performed using GenStat 19th Edition (VSN International). Graphical representations were produced in Python 3.11 (matplotlib v3.8, 300 dpi).

3. RESULTS

3.1 Plant Height

ANOVA revealed that plant height was not significantly different at 30 DAT (pre-application; Table 1), confirming treatment homogeneity at baseline. After initiation of bio-stimulant sprays, significant height differences emerged at 60, 90 DAT, and at harvest (Fig. 1). T5 (5 ml L^{-1}) consistently produced the tallest plants at 60 DAT (68.17 cm), 90 DAT

(102.53 cm), and at harvest (128.81 cm), exceeding T1 (56.25, 92.77, and 114.00 cm, respectively) by 21.2%, 10.5%, and 13.0%. T5 was statistically at par with T4 (3 ml L^{-1}; 125.63 cm) and T3 (2.5 ml L^{-1}; 123.24 cm). The enhanced internode elongation under bio-stimulant treatments is attributable to the cytokinin-like and auxin-potentiating activity of humic substances and amino acid fractions (Nardi et al., 2016).

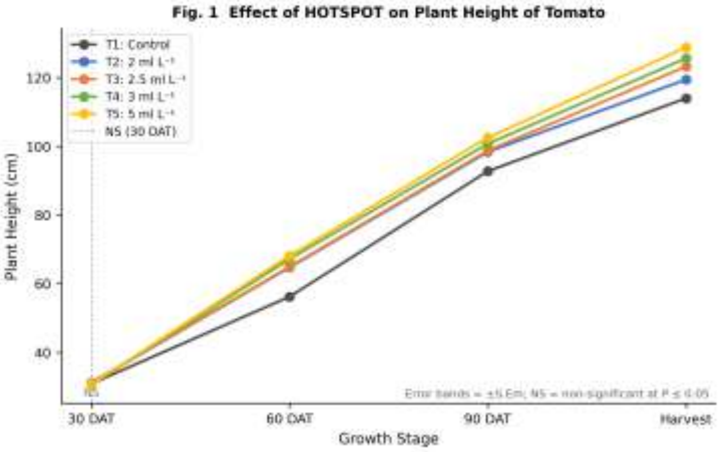

Fig. 1. Effect of HOTSPOT bio-stimulant on plant height (cm) of tomato at different growth stages. Error bands represent ±S.Em. NS at 30 DAT indicates non-significant differences (P ≤ 0.05).

3.2 Number of Branches per Plant

Branch number was significantly influenced by HOTSPOT at all observed stages - 60 DAT, 90 DAT, and harvest (Fig. 2A). T5 attained the highest branch count at harvest (15.47), surpassing T1 (11.15) by 38.7%, a difference exceeding the CD value (0.78). T4 (14.85) and T3 (13.20) were ranked second and third. Enhanced branching under bio-stimulant treatment increases the number of sympodial units available for fruit-bearing clusters, directly expanding the yield sink capacity. This finding is consistent with Shehata et al. (2012), who reported 25-35% increases in branch number of tomato following foliar application of bio-stimulants based on chitosan and yeast extract.

3.3 Stem Diameter

Stem diameter did not differ significantly at 30 DAT but diverged significantly from 60 DAT onwards (Fig. 3A). At harvest, T5 recorded the largest stem diameter (1.573 cm), exceeding T1 (1.270 cm) by 23.9%. T4 (1.490 cm) and T3 (1.333 cm) were intermediate. Greater stem diameter reflects thicker vascular bundles, which enhances phloem transport capacity and the supply of photosynthates to developing fruits.

3.4 Number of Leaves per Plant

Number of leaves per plant showed no significant treatment effect at 30 DAT but differed significantly from 60 DAT onwards (Fig. 2B). At harvest, T5 had 25.35 leaves $plant^{-1}$ versus 19.76 in T1 (+28.3%). T4 (23.86) was at par with T5. Greater leaf number directly augments the light-intercepting area and total canopy photosynthesis, providing more assimilates for fruit development.

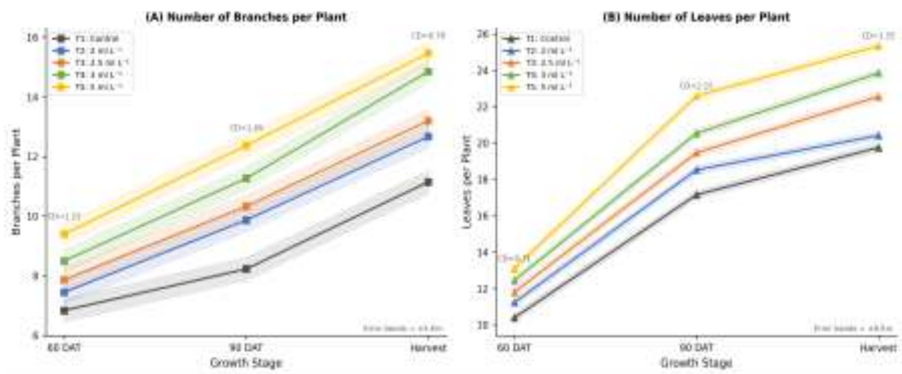

Fig. 2. Effect of HOTSPOT bio-stimulant on (A) number of branches per plant and (B) number of leaves per plant of tomato. Error bands represent ±S.Em; CD values at each time point are indicated above the respective stage.

3.5 Leaf Area per Plant and Leaf Area Index

Leaf area per plant and LAI were not significantly affected at 30 DAT but diverged significantly from 60 DAT onwards (Fig. 4). At harvest, T5 recorded the largest leaf area (218.3 cm^2 $plant^{-1}$) and highest LAI (0.0404), exceeding T1 (178.1 cm^2, LAI 0.0330) by 22.6% and 22.4%, respectively. T4 (194.8 cm^2, LAI 0.0361) was at par with T5. Although absolute LAI values are low, reflecting the vine-type indeterminate growth habit of tomato at 50 × 50 cm spacing, the relative differences are agronomically meaningful - each 10% increase in LAI translates proportionally to greater radiation use efficiency (Heuvelink, 2005).

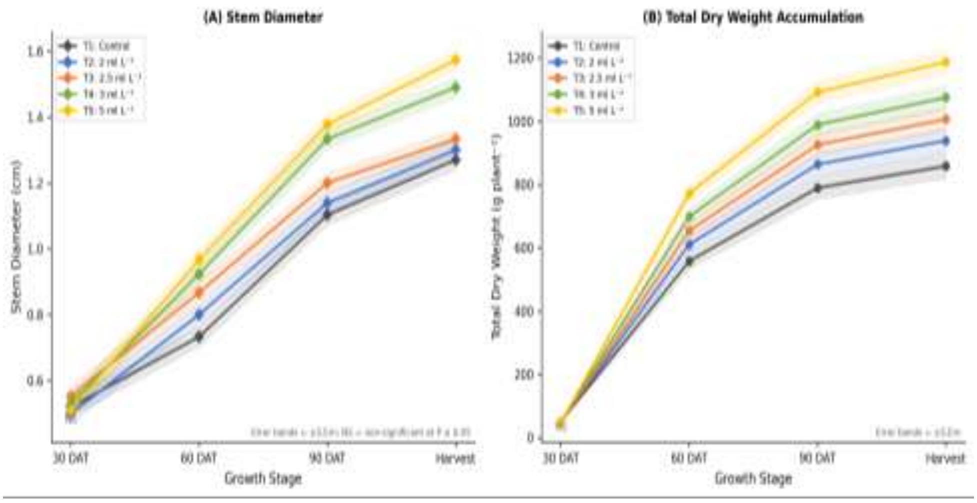

Fig. 3. Effect of HOTSPOT bio-stimulant on (A) leaf area per plant (cm² plant⁻¹) and (B) Leaf Area Index (LAI) of tomato. Error bands represent ±S.Em. NS at 30 DAT indicates non-significant differences.

3.6 Total Dry Weight per Plant

Total dry weight did not differ significantly at 30 DAT but was significantly higher in bio-stimulant treatments from 60 DAT onwards (Fig. 3B). At harvest, T5 (1187.50 g plant^{-1}) exceeded T1 (858.47 g plant^{-1}) by 38.3%, while T4 (1075.34 g) and T3 (1006.65 g) were intermediate. The progressive accumulation of dry matter in treated plants reflects sustained improvements in source (leaf area, photosynthesis) and sink (branch and fruit number) capacity, consistent with the framework proposed by Rouphael et al. (2015) for bio-stimulant action in horticultural crops.

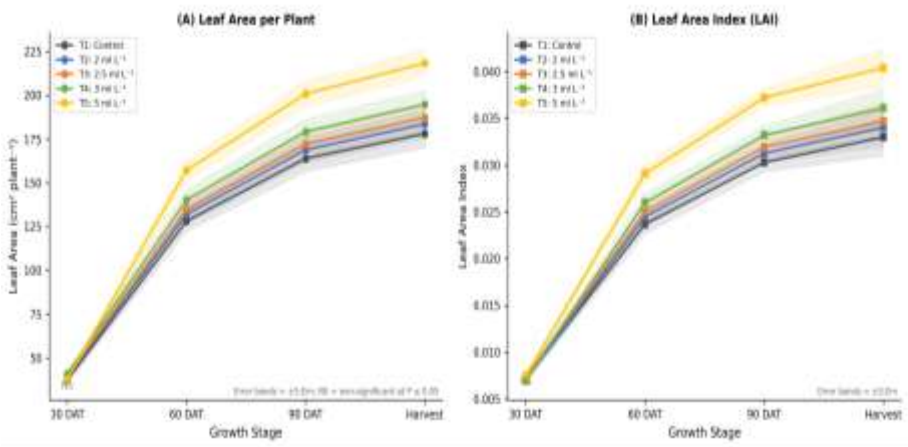

Fig.4. Effect of HOTSPOT bio-stimulant on (A) stem diameter and (B) total dry weight accumulation in tomato. Error bands represent ±S.Em. NS at 30 DAT indicates non-significant differences.

3.7 Yield and Yield Attributes

All yield attributes were significantly influenced by treatments (Table 2; Figs. 5 and 6). T5 achieved the highest values for fruit weight (110.74 g; +16.5% over T1), fruit diameter (6.80 cm; +16.6%), number of fruits per plant (85.00; +19.7%), and fruit volume (179.93 cc; +16.6%). T4 was at par with T5 for fruit diameter, fruit number, and fruit volume, but differed significantly from T1. T5 recorded the highest yield plant^{-1} (9.43 kg) and hectare yield (252.98 q ha^{-1}), exceeding T1 (6.55 kg plant^{-1}; 196.14 q ha^{-1}) by 43.9% and 28.97%, respectively. The yield response to increasing HOTSPOT concentration follows a diminishing-returns curve beyond 3 ml L^{-1}, consistent with saturation kinetics in bio-stimulant dose-response studies (Rouphael and Colla, 2020).

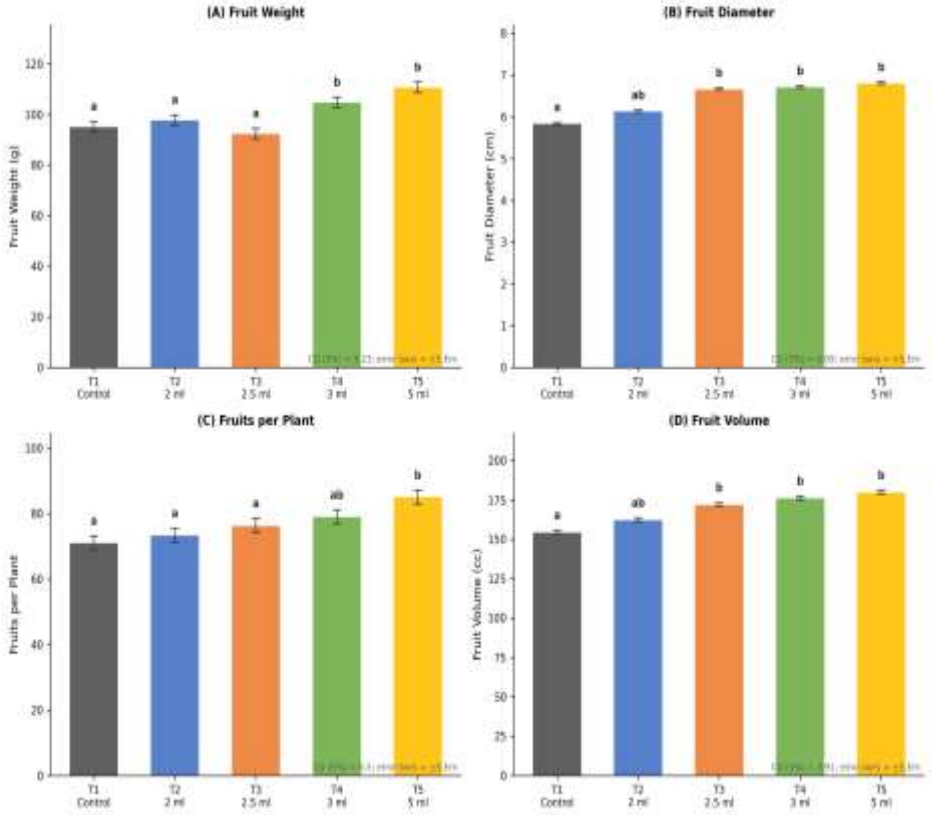

Fig. 5. Effect of HOTSPOT bio-stimulant on yield attributes of tomato: (A) fruit weight, (B) fruit diameter, (C) number of fruits per plant, and (D) fruit volume. Error bars represent ±S.Em. Significance letters (a, b) above bars indicate statistical groups at P ≤ 0.05.

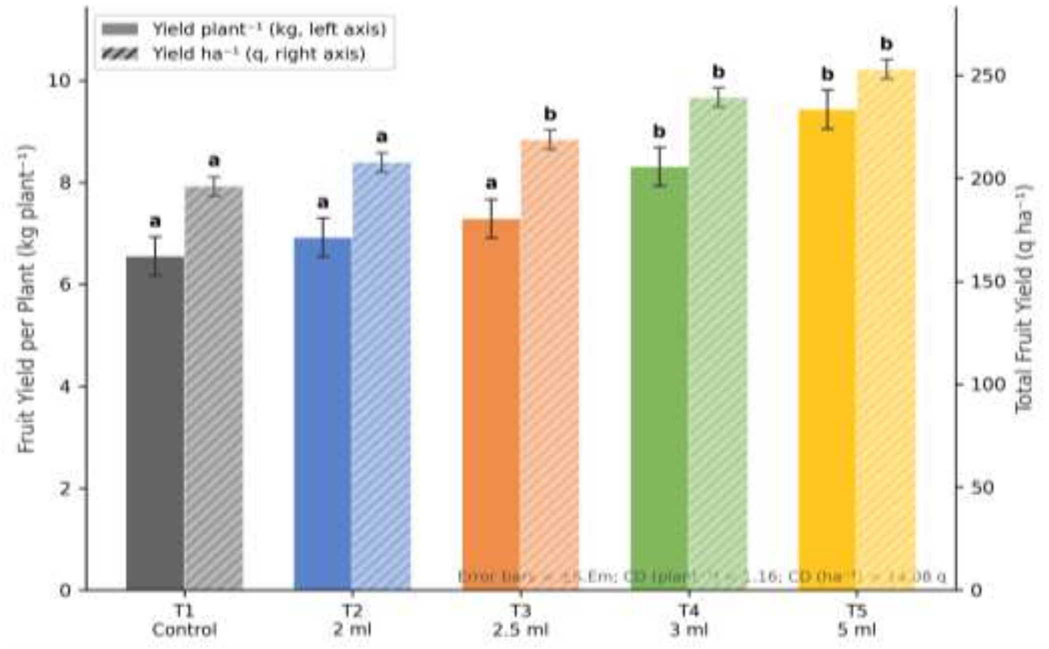

Fig. 6. Effect of HOTSPOT bio-stimulant on fruit yield per plant (kg plant^{-1}, left axis, solid bars) and total fruit yield (q ha^{-1}, right axis, hatched bars) of tomato. Error bars represent ±S.Em. Significance letters above bars indicate statistical groups at P ≤ 0.05.

3.8 Nutrient Uptake

N, P, and K uptake were all significantly enhanced by HOTSPOT treatments (Fig. 7). T5 recorded the highest N uptake (98.53 kg ha^{-1}; +22.8% over T1), P uptake (49.93 kg ha^{-1}; +20.2%), and K uptake (112.76 kg ha^{-1}; +15.4%). T4 was at par with T5 for all three nutrients. The disproportionately large yield gain (~29%) relative to N uptake gain (~23%) suggests that HOTSPOT improved nutrient use efficiency (NUE) in tomato, a pattern attributed by Lucini et al. (2015) to amino acid-mediated enhancement of enzyme activities governing nitrate assimilation and phosphate solubilization.

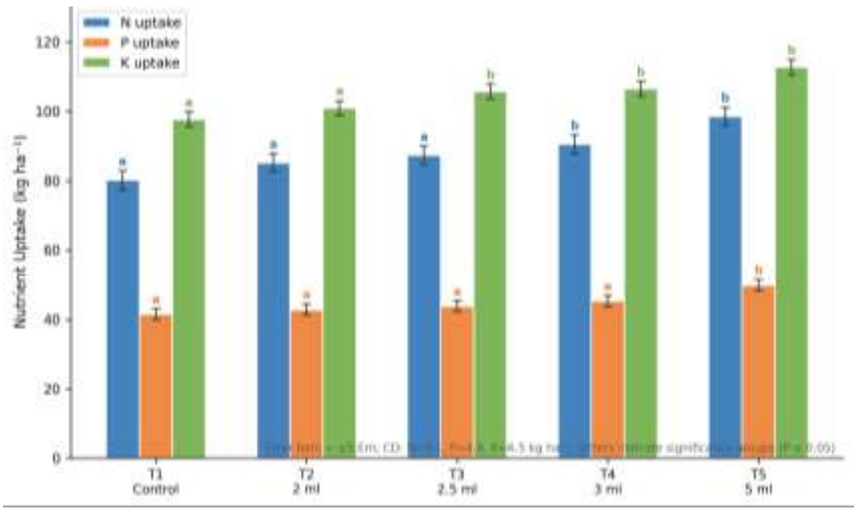

Fig. 7. Effect of HOTSPOT bio-stimulant on N, P, and K uptake (kg ha^{-1}) by tomato. Error bars represent ±S.Em. CD values: N = 8.10, P = 4.80, K = 6.50 kg ha^{-1}. Significance letters (a, b) above bars indicate statistical groups at P ≤ 0.05.

3.9 Fruit Quality Parameters

TSS, vitamin C, and lycopene content were all significantly affected by treatments (Fig. 8). T5 recorded the highest TSS (4.81 °Brix; +2.8% over T1), vitamin C (18.53 mg 100 g^{-1}; +2.6%), and lycopene (3.96 mg 100 g^{-1}; +7.0%). T4 was at par with T5 for all quality parameters. The 7.0% increase in lycopene - the primary antioxidant carotenoid in tomato - is particularly noteworthy. Enhanced lycopene accumulation under bio-stimulant treatment may reflect both the improved fruit size and the activation of the isoprenoid biosynthesis pathway through auxin-mediated gene expression (Heuvelink, 2005).

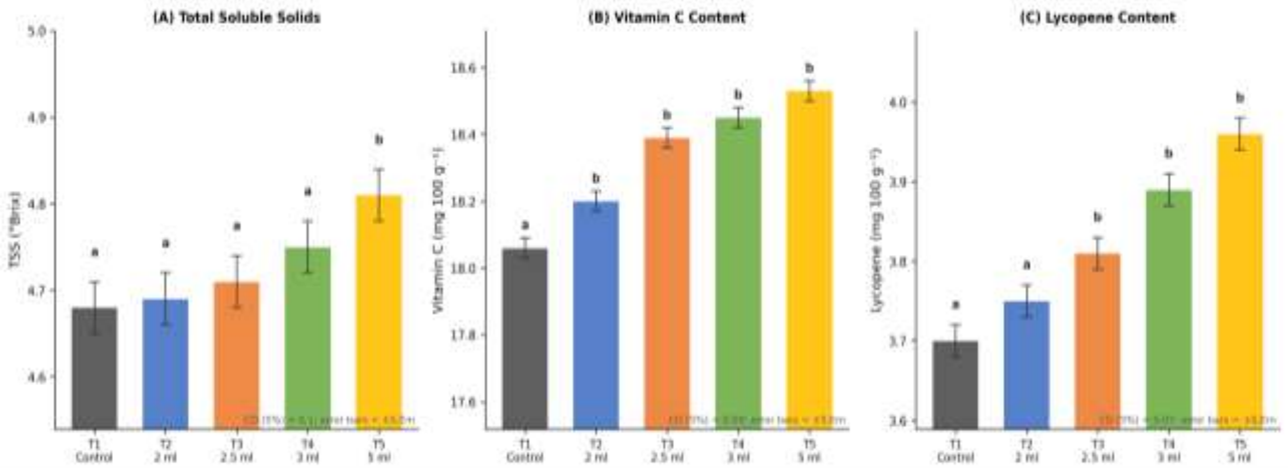

Fig. 8. Effect of HOTSPOT bio-stimulant on fruit quality parameters of tomato: (A) TSS (°Brix), (B) Vitamin C (mg 100 g^{-1}), and (C) Lycopene content (mg 100 g^{-1}). Error bars represent ±S.Em. Significance letters (a, b) indicate statistical groups at P ≤ 0.05.

3.10 Phytotoxicity Assessment

No phytotoxic symptoms were observed on tomato plants at any application dose across all observation dates (3, 7, 10, and 14 days after each spray). All phytotoxicity scores remained at 0 on the 0-10 scale for all eight parameters assessed (leaf injury, wilting, vein clearing, necrosis, chlorosis, stunting, epinasty, and hyponasty), confirming the complete safety of HOTSPOT for foliar use on tomato up to 5 ml L^{-1}.

3.11 Cost-Benefit Analysis

Cost-benefit analysis revealed that all HOTSPOT treatments were profitable relative to untreated control (Table 3; Fig. 9). T4 (3 ml L^{-1}) achieved the highest C:B ratio (1:6.76), generating ₹60,188 net profit ha^{-1} from an investment of ₹8,900 ha^{-1}. T5 (5 ml L^{-1}) had the highest absolute net profit (₹78,494 ha^{-1}) but a lower C:B ratio (1:6.28) due to the higher product cost at 5 ml L^{-1}. T3 returned a C:B ratio of 1:3.54, while T2 returned the lowest ratio (1:1.61), indicating marginal returns at sub-optimal doses. These results collectively recommend T4 as the economically optimal treatment.

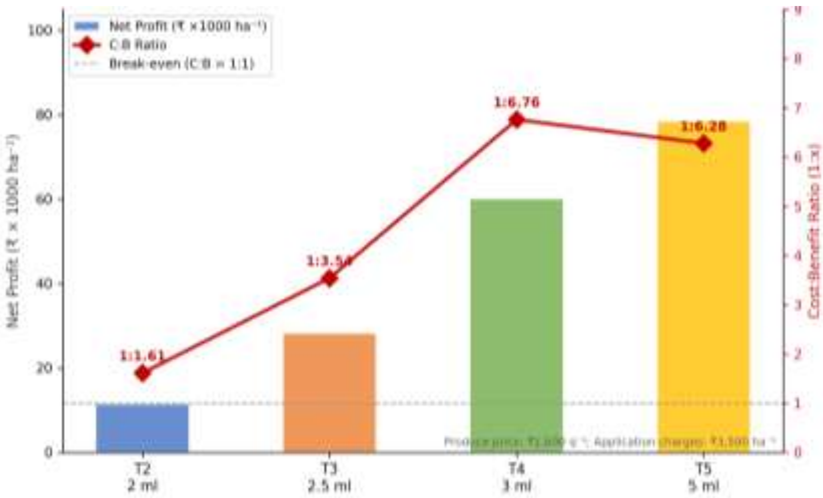

Fig. 9. Cost-benefit ratio and net profit (₹ × 1000 ha^{-1}) from HOTSPOT bio-stimulant application on tomato. Diamond markers (red line) indicate C:B ratio (right axis); bars indicate net profit (left axis). Dotted line marks break-even (C:B = 1:1).

4. DISCUSSION

The present study establishes a consistent and statistically robust dose-response relationship between HOTSPOT bio-stimulant concentration and agromorphological performance of tomato under Eastern Dry Zone conditions. The hierarchical ordering T5 > T4 > T3 > T2 > T1 across virtually all measured parameters is a hallmark of true bio-stimulant activity, where increasing concentrations of bioactive molecules progressively activate plant growth-promoting pathways up to a saturation point.

The growth improvements - particularly the 38.7% increase in branches per plant and 38.3% increase in total dry weight at harvest under T5 - are substantially larger than those typically reported for single-component bio-stimulants (15-25%; Bulgari et al., 2015), suggesting that HOTSPOT may contain synergistically acting components. Multi-component formulations have been shown to stimulate both auxin-mediated cell elongation (contributing to height and stem diameter gains) and cytokinin-mediated axillary bud break (contributing to branching), consistent with the dual effects observed here.

The 28.97% increase in total fruit yield (196 to 253 q ha^{-1}) at the highest dose places this study's magnitude of response at the upper end of reported ranges for bio-stimulant effects on tomato. Rouphael and Colla (2020), reviewing 120 published studies, found a median yield increase of 12-15% for foliar bio-stimulants in Solanaceous vegetables. The larger effect observed here may reflect the particularly responsive soil-climate environment: Alfisol soils with moderate organic matter and low N supply create conditions where any growth-promoting input is more likely to produce visible yield responses.

The fruit quality response is agronomically and nutritionally significant. Lycopene is a potent dietary antioxidant with documented roles in reducing cardiovascular disease and prostate cancer risk; a 7% improvement in fruit lycopene content represents a meaningful health benefit. The mechanism is likely related to bio-stimulant-induced upregulation of phytoene synthase, the rate-limiting enzyme in carotenoid biosynthesis, as reported by Yakhin et al. (2017) for amino acid-based bio-stimulants.

From an economic standpoint, the declining C:B ratio from T4 (1:6.76) to T5 (1:6.28) despite continued yield gains illustrates the classic diminishing marginal returns to input. The C:B ratio of 1:6.76 is exceptionally favorable compared to typical agrochemical inputs in tomato production, which rarely exceed 1:3 (Kauffman et al., 2007), underscoring the economic attractiveness of HOTSPOT at the 3 ml L^{-1} rate.

5. CONCLUSION

This study provides the first replicated multi-dose field evidence for the agronomic and economic efficacy of HOTSPOT bio-stimulant in tomato under the Eastern Dry Zone of Karnataka. Four foliar applications at critical phenological stages significantly enhanced vegetative growth (plant height, branching, leaf area, dry matter accumulation), fruit yield (up to +29% over control at 5 ml L^{-1}), fruit quality (lycopene +7%, vitamin C +2.6%, TSS +2.8%), and N-P-K uptake. HOTSPOT was completely free of phytotoxic effects at all tested concentrations. The application of HOTSPOT at 3 ml L^{-1} at 30, 45, 60, and 75 DAT is recommended as the optimal dose for commercial tomato production, delivering the highest cost-benefit ratio (1:6.76). Future research should investigate the molecular mode of action of HOTSPOT, its interactions with soil microbiota, and its performance across different tomato varieties, irrigation regimes, and agroclimatic zones.

Author Contributions

K.S.S.: conceptualization, experimental design, field supervision, manuscript drafting, review and editing. A.R.: data analysis, review and editing.

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Conflict Of Interest
The authors declare no conflict of interest.

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