Current Horticulture is indexed in the...

- AGRINDEX, published by the FAO, Rome; the Science Citation Index and the Current Contents (Agriculture, Biology and Environmental Sciences), published by the Institute of Scientific Information, Philadelphia
- Abstracting journals of the Centre for Agriculture and Biosciences International
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Published by the Society for Horticultural Research and Development, SD-70, Shastri Nagar, Ghaziabad, and printed at M/s Chandu Press, 469, Patparganj Industrial Estate New Delhi, E-mail: chandupress@gmail.com

Editor: Dr Som Dutt

RNI No. UPENGO3865/24/1/2013-TC

ISSN (Print) : 2347-7377
ISSN (Online) : 2455-7560

Current Horticulture

(a journal dedicated for the advancement of Horticultural science)

Vol. 14 No. 2, July-September 2026



www.currenthorticulture.com

(www.currenthorticulture.com)

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Aims and Scope: The ***Current Horticulture*** is a peer-reviewed and free open-access journal, published quarterly by a non-profit making organization, Society for Horticultural Research and Development (SHRD),Ghaziabad, Uttar Pradesh, India. The prime objective of the journal is to disseminate the emerging advancements in horticultural science. The Journal publishes research papers, review papers, short communications, special issues, and breakthrough reports concerning disciplines of biotechnology, plant breeding, conservation and evaluation of germplasms, soil science, crop agronomy, crop physiology, biochemistry, entomology, plant pathology, post-harvest management , value- addition, waste utilization and climate smart horticulture.

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CURRENT HORTICULTURE

Vol 14, No. 3, July-September 2026

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Current Horticulture 14(3): 3-18, July–September 2026

Research Review Article

DOI: 10.5958/2455-7560.2026.00032.4

Received: 14 June 2026; Revised: 22 August 2026: Accepted: 03 September 2026

Breeding tomato (*Solanum lycopersicum*) for processing quality: integrated perspectives

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Abstract

Tomato (*Solanum lycopersicum* L.) is a globally important vegetable crop with significant relevance in both fresh consumption and processing industries. Despite India being one of the largest producers, the proportion of tomatoes utilized for processing remains negligible, highlighting the need for targeted breeding strategies. Processing tomatoes require a unique combination of morphological, biochemical, and molecular traits such as high total soluble solids (TSS), deep red colour, high lycopene content, optimal acidity, firmness, thick pericarp, and suitability for mechanical harvesting. This review comprehensively examines key traits influencing processing quality, including fruit morphology, plant architecture, biochemical composition, and physiological attributes such as ripening behavior and stress tolerance. The genetic basis of these traits is discussed with emphasis on major genes and quantitative trait loci (QTLs) controlling sugar accumulation, acidity, colour, firmness, and viscosity. Advances in molecular breeding approaches, including marker-assisted selection (MAS), genome-wide association studies (GWAS), and CRISPR/Case-based genome editing, have accelerated the development of superior processing cultivars. Integration of wild germplasm, genomic tools, and multi-environment testing is essential to overcome challenges such as yield quality trade-offs and climate stress. The review underscores the importance of a multidisciplinary approach to develop high-yielding, stress-resilient, and industry-oriented tomato cultivars, thereby strengthening the processing sector and enhancing farmers' profitability.

Key words: Biochemical, Breeding, Genomics, Processing, Tomato

Tomato (*Solanum lycopersicum* L.) is one of the most significant vegetable crops, globally utilized extensively for both fresh consumption and a wide array of processed products, including juice, ketchup, paste, and purees (NAAS, 2022). Often described as "protective food" (Kumar *et al.,* 2013; Somappa *et al.,* 2013), it holds immense agricultural and economic significance (Vats *et al.,* 2020) which is matched by its nutritional value, offering high levels of vitamins, minerals and bioactive compounds such as carotenoids, polyphenols and most notably lycopene, which is known for its anti-cancerous effects (Canene-Adams *et al.,* 2005; Omoni and Aluko, 2005; Kun *et al.,* 2006). Besides carotenoids, tomato is rich in natural antioxidants (Davies and Hobson, 1981) that inhibit the oxidation of lipids and other molecules by preventing oxidative chain reactions (Velioglu *et al.,* 1998). Tomato is one of the most cultivated vegetables in the world, with a global production of 188.49 million tonnes from 5.12 million ha area at the productivity rate of 36.80 t/ha (FAOSTAT, 2024). The leading producer is China, followed by India, which produced around 21.32 million tonnes, contributing 11.3% of global tomato production (FAO STAT, 2024) (Fig. 1).

Around 40-46 million tonnes (20-25 %) of global tomatoes are processed into value-added products, whereas India processes very low, i.e. < 1% of its total production (NAAS, 2022; Tiwari *et al.,* 2022). This high demand for processing tomatoes, which is driven by industrial standards to maximize product recovery and manufacturing efficiency, highlights a fundamental genetic and phenotypic dichotomy between fresh-market and processing tomato cultivars (Chattopadhyay *et al.,* 2013). While fresh-market breeding predominantly emphasizes visual aesthetics, uniform ripening, and prolonged shelf-life, processing tomatoes are bred for a set of morphological and physiochemical characteristics that are less important in table varieties, in order to maximize product recovery and manufacturing efficiency (Stommel *et al.,* 2005).

The tomato processing industry relies on cultivars with specific quality attributes that ensure high extraction efficiency, desirable sensory properties and superior stability during manufacturing of puree, paste, ketchup, juice and canned products. Key processing-related traits include high total soluble solids (TSS) (> 5.5 °Brix), deep red colour (a/b, Hunter colour value: > 1.95), lycopene content (> 8.5 mg/100 g), balanced titratable acidity (< 0.4 %), low pH (< 4.40), fruit firmness/ texture (> 4 N), thick pericarp thickness (> 0.4 cm), high viscosity/ consistency (7-14 Botswick, cm/30 sec), determinate, oval shape, small locule (2-3), pulp (65-75%), low seed content, small core, no radial and concentric cracking, elongated, smooth surface/free from wrinkles and

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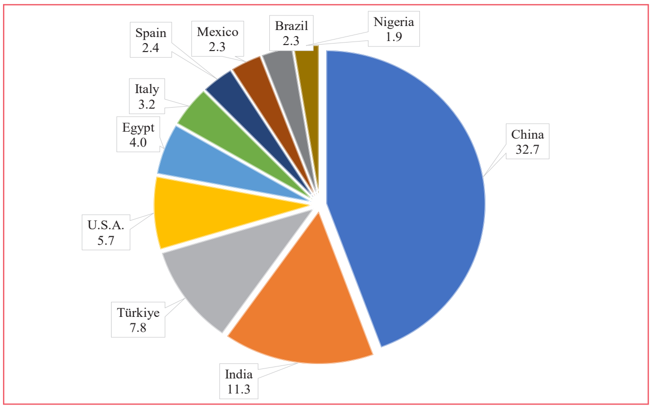

Fig. 1. Top ten tomato-producing countries (% share) (FAO STAT, 2024)

high alcohol-insoluble solids so on (Tiwari *et al.,* 2026) (Table 1).

Table 1: Processing criteria of tomato

Processing trait	Standard values desired by processors
TSS	>5.5°Brix
Colour value	>1.95
Acidity	0.3-0.4%
Titrable acidity	6-8 mmol/L
pH	< 4.30
Texture/firmness	>8.00
Lycopene	>12 mg/100g FW
Viscosity	12-14 Bostwick cm/30 sec
Vitamin C	>25 mg/100g
Pericarp thickness	>0.4cm
Fruit weight	>80g
Juice yield	>70%
No. of locules	2-4
Sugar : acid ratio	15:1
Yield	>75-80 t/ha
Fruit colour	Deep red
Fruit maturity	Concentrated fruit maturity
Vine storability	Prolonged
Pedicel	Jointless
Fruit shoulder	Uniform green

Source: Tiwari *et al.* (2026)

Tomato breeding for processing required integration of traits/genes, *viz.* determinate/ self-pruning (*sp*), concentrated fruit maturity (*cfm*), jointless (*j-2*), uniform ripening (*u*), single flower truss (*SFT*), sucrose accumulator (for high TSS) (*sucr*), old gold crimson (og^c), intense pigment (deep red) (*Ip*), and high pigment-2 (high lyconene) (*hp-2*) so on. In addition under the changing climate scenario, resistance to biotic stresses like diseases (tomato leaf curl virus, late blight, early blight, bacterial leaf spot and root knot nematode) and pest (white fly) resistance, and abiotic stresses (heat, drought and salinity) are also important.

The processing tomato varieties tend to have the determinate growth habit that is regulated by the self-pruning gene (*SP*), making it possible to obtain plants with synchronized maturity and firmness to harvest them in one pass using the machinery (Rothan *et al.,* 2019) and must have firm, blocky or oval fruits, with a thick pericarp to withstand the mechanical stress of bulk transportation and industrial handling without compromising tissue integrity (Chattopadhyay *et al.,* 2013; Rothan *et al.,* 2019). In terms of biochemical traits, the economic viability of tomato processing is heavily reliant on high Total Soluble Solids (TSS), above 5.0° Brix because it drastically decreases the thermal energy and time required to concentrate paste (Kumar *et al.,* 2019) and processors prefer high titratable acidity and a low pH (<4.4) to ensure microbial food safety and flavour balance, as well as elevated lycopene concentrations (> 10 mg/100 g fresh weight) that impart the deep-red pigmentation required for high-quality commercial products (Chattopadhyay *et al.,* 2013).

Even with these defined parameters, developing elite processing cultivars is subject to many agronomic bottlenecks, such as negative genetic correlation between high yield and high metabolite concentration, known as the yield-quality trade-off (Gur and Zamir, 2004), and increasingly adverse effects of climate change that manifest as extreme drought, rising temperatures, and soil salinity that threaten reproductive physiology and biochemical stability of crop (Alsamir *et al.,* 2021). Mild stress conditions may improve certain quality traits, including total soluble solids and secondary metabolites, due to concentration effects; however, severe stress significantly reduces plant growth and overall yield (Rigano *et al.,* 2016). Therefore, improvement programmes should combine conventional breeding with modern approaches such as marker-assisted selection (MAS), quantitative trait loci (QTL) mapping and CRISPR/Case-based genome editing to develop cultivars that are both stress tolerant and capable of maintaining high yield and processing quality (Rothan *et al.,* 2019; Wang *et al.,* 2019).

To address these challenges, tomato improvement requires a combination of classical breeding and modern genomic tools. The recent progress in marker-assisted selection coupled with modern genomics tools and emerging CRISPR/Cas-based genome editing has enabled targeted genetic improvement of tomato. Strengthening the use of wild relatives (*S. pennellii*, *S. pimpinellifolium* and *S. habrochaites*) for trait introgression, integrating multi-environment testing, and deploying genomic selection can accelerate breeding gains. Moreover, genome-wide association studies (GWAS) using diverse panels have identified novel alleles/QTLs in tomato breeding. Overall, the convergence of conventional breeding and modern genomics is reshaping the landscape of processing tomato improvement. The identification of robust QTLs, trait-specific candidate genes and predictive genomic markers would form the foundation for developing next-generation processing tomato cultivars with better fruit quality and fitting to industrial standards. For future advancement, India requires stronger public–private partnerships, dedicated processing tomato breeding programmes tailored to regional agro-industrial needs, and enhanced farmer–industry linkage through efficient value chains. These innovations will be pivotal to develop resilient, high-quality processing tomato varieties that can support sustainable growth of India's processing sector and improve farm profitability.

Morphological traits affecting processing quality

Breeding for processing tomato quality has historically relied on phenotypic selection and introgression of favourable alleles from adapted cultivars and wild relatives such as *S. pennellii*, *S. pimpinellifolium* and *S. habrochaites*. Wild donors have been particularly valuable for enhancing TSS, acidity, firmness and stress tolerance. However, many processing traits exhibit polygenic inheritance with strong genotype × environment interactions, making them difficult to improve solely through conventional selection. The advent of molecular markers, linkage mapping and introgression line (IL) populations revolutionized the identification of quantitative trait loci (QTLs) controlling fruit quality. Landmark discoveries such as the Brix9-2-5 QTL and its candidate gene *LIN5*, major-effect loci like *ogc*, and ripening regulators including *rin*, *nor* and *alc* provided breeders with molecular targets for improving fruit solids, colour and firmness.

The integration of genomic resources has further accelerated processing tomato improvement. High-density SNP arrays, genotyping-by-sequencing (GBS) and whole-genome resequencing have enabled fine-mapping of QTLs for sugars, acids, lycopene content, pectin metabolism and viscosity. Genome-wide association studies (GWAS) using diverse panels have identified novel alleles for fruit quality, while meta-QTL and haplotype analyses have refined large-effect loci into narrow, breeder-friendly intervals. Candidate genes located within these regions, such as those involved in carbohydrate metabolism (invertases, sucrose synthases), carotenoid biosynthesis (PSY1, ZISO, CRTISO, CYC-B), and cell-wall remodeling (polygalacturonase, pectin methylesterase, expansins), now guide marker-assisted and genomic selection strategies. Overall, the convergence of classical breeding, quantitative genetics and modern genomics is reshaping the landscape of processing tomato improvement. The identification of robust QTLs, trait-specific candidate genes and predictive genomic markers now forms the foundation for developing next-generation processing tomato cultivars with greater quality, consistency and industrial performance.

The morphological architecture of tomato plant and its fruit play a critical role in determining its suitability for processing applications (Bai and Lindhout, 2007; Ortega-Salazar *et al.,* 2025). Accordingly, processing tomatoes are bred for specific structural and anatomical traits such as, firm texture, high total soluble solids, uniform ripening, and a compact plant habit to enhance industrial efficiency and facilitate mechanical harvesting (Lin *et al.,* 2014; Kyriacou and Rouphael, 2018). Although these traits are heritable, their phenotypic expression is also influenced by environmental conditions. Growth habit, stem strength, and fruit uniformity are important traits for breeding programs, and studies have demonstrated strong positive correlations between morphology and soluble solids, viscosity, and recovery percentage.

Fruit size, shape and locular cavity

The physical attributes including fruit shape and internal anatomy have been found to play a significant role in determining processing effectiveness in tomatoes (Rodríguez *et al.,* 2021). For instance, processing industries tend to use pear-, oval-, oblong-, blocky- or Roma-shaped varieties than round varieties, partly owing to their low locule number (2–4) to enhance paste concentration efficiency with reduced energy input (Chattopadhyay *et al.,* 2013). The differences in internal anatomy between various tomato varieties are related to their varying numbers of locules and pericarp ratios. Major QTLs controlling fruit shape and locule number include *lc* and *fas* (Lin *et al.,* 2014). The locule cavity size impacts on fruit composition by contributing to acidity while the pericarp is responsible for fruit sugar content and aroma production. A small locule cavity, therefore, means that the pericarp ratio will be high, thus increasing TSS concentration and minimizing dehydration during processing (Chattopadhyay *et al.,* 2013).

The shape of fruit is primarily governed by genetic determinants, where genes like OVATE and SUN have an important function in the determination of elongated fruits (Causse *et al.,* 2002). Fruit size is, on the other hand, affected by both genetic and environmental factors, as well as agricultural techniques used. The development of pericarp first takes place by means of cell division (10-25 days after anthesis) and subsequently by cell expansion (Ho, 1996; Bertin *et al.,* 2003; Bertin and Génard, 2018).

Pericarp thickness

A thick pericarp (more than 0.50 cm) is one of the important considerations in the processing of tomatoes (Chattopadhyay *et al.,* 2013). The increased resistance against mechanical damage by having a thick pericarp reduces loss of fruits during transportation and other processing activities. Thick pericarp has also been noted to be positively correlated with recovery percentage and can be used as a selective trait in the breeding programme (Kumar *et al.,* 2019). Pericarp development helps to ensure fruit development, mainly determining its size (Ho, 1996). Features such as anatomical characteristics, especially the thickness of the pericarp, affect texture and firmness of fruits (Aurand *et al.,* 2012). In the earlier stages of fruit development, cells of the inner and radial pericarp act as storage organs for starch, reaching their maximum level at 10-25 days after anthesis and are later broken down to soluble sugars (Schaffer and Petreikov, 1997). Cell expansion in later stages depends on water movement by the xylem and phloem systems and is dependent on sugar metabolism and turgor pressure.

Fruit firmness and mechanical handling resilience

A high level of firmness is required for tomatoes used for processing (Nie *et al.,* 2024). Such a feature affects not only consumer preferences but also the storage and transportation processes (Causse *et al.,* 2010; Seymour *et al.,* 2013). The fruits that have firmness can survive mechanical harvesting, handling and transportation without sustaining damages. The lack of firmness leads to cell disintegration, accelerated respiration, the development of ethylene, and susceptibility to infections (Held *et al.,* 2015). During ripening, the decrease in the level of firmness is caused mostly by the degradation of the cell wall material, especially the degradation of pectins of the middle lamella by enzymes like polygalacturonase (PG) and pectate lyases (PL) (Quinet *et al.,* 2019). Tissue thickness, cell size and turgor pressure affect the firmness of the fruits in the development process. Additionally, genetic traits have their impact on this trait, since such QTLs as (*fir5.1*) located on chromosome 5 affect firmness, making it more pronounced in processing tomatoes than fresh tomatoes (Lin *et al.,* 2014). Thus, breeding programs should include increasing the firmness and thickening of tomato walls to prevent softening (Nie *et al.,* 2024).

Plant architecture: determinate growth and jointless pedicels

The combination of a determinate compact habit, concentrated maturity, and jointless pedicels is the necessary requirement for mechanical once-over harvesting that reduces labor and provides a stable supply chain to the processing units (Tiwari *et al.,* 2022). The plant architecture of tomato crops is thus equally as vital as its fruit attributes in industrial cultivation practices. In contrast to fresh market tomatoes, which usually have an indeterminate or semi-determinate growth pattern, processed tomato varieties usually display determinate growth. The reason behind this is that the growth pattern is regulated by the self-pruning gene which restricts the vegetative growth and produces a bushy plant with enough leaf surface to shade the fruits from burning (Rothan *et al.,* 2019). Importantly, this highly managed growth habit directs the plant's metabolic energy predominantly toward reproductive development, thereby promoting concentrated fruit maturity (CFM), a physiological phenomenon in which most fruits ripen simultaneously on the vine (Rothan *et al.,* 2019). Processing varieties must also have a jointless pedicel, a trait in which the fruit readily separates from the vine without the stem or calyx remaining attached to the fruit, to fully take advantage of CFM (Tiwari *et al.,* 2022). Breeding targets for processing tomato are given in Table 2.

Promising lines for processing quality: The ICAR-IIVR, Varanasi, has developed tomato genotypes (hybrids/OP) with high TSS such as VRTH-24-58 (5.95 °Brix), VRTH-24-41 (5.93 °Brix), VRTH-24-56 (5.91 °Brix), VRTPH-24-18 (5.75 °Brix), VRTPH-24-5 (5.71 °Brix) and VRTH-24-19 (5.63 °Brix). Among advance hybrids, VRTH-16-4 (recently released as Kashi Shreshth) (4.5 °Brix) is found suitable for dual purpose i.e. both fresh and processing purpose. A few promising OP lines possessing high TSS are EC-620456 (5.93 °Brix), EC-62032 (5.73 °Brix), (5.73 °Brix), VRT-67 (5.70 °Brix), AVTO-2101 (5.60 °Brix), EC-715384 (5.60 °Brix) and VRT-06 (5.26 °Brix). Besides, there are many more lines in pipeline under evaluation stage (Fig. 2).

Biochemical traits for processing

The biochemical make-up of tomato fruit is a major determinant of its adaptability to processing because it influences the nutritional quality, palatability, and efficiency of processing (Bertin and Génard, 2018; Amr and Raie, 2022). In contrast to fresh-market varieties which are graded according to visual attributes and texture, those grown for processing are selected by certain physicochemical factors. Factors such as total soluble solids, colour, pH, and texture are crucial because they affect the yield, processing efficiency, and quality of products such as paste, puree, ketchup, and juice (Amr and Raie, 2022).

Table 2: Breeding targets for processing tomato

Trait category	Specific trait	Target value	Breeding objective	Rationale for processing industry
Fruit physical traits	Plant growth habit	Determinate, compact	Improve uniform ripening and mechanical harvesting	Allows synchronized harvest and reduces labour
	Fruit shape	Oval/ roma/ pear-shaped	Standardize fruit size for processing	Reduces sorting loss; suits pulping equipment
	Fruit firmness	High firmness (≥ 5–6 N)	Delay softening	Essential for transport and peeling
	Pericarp thickness	≥ 5–7 mm	Increase pulp yield	Higher recovery for paste/ puree
	Placenta & locule number	2–3 locules, thick walls	Reduce seediness	Improves puree smoothness
	Seed content	Low	Minimize seed residues	Ensures high-quality pastes and sauces
	Fruit cracking resistance	High	Prevent pre-harvest losses	Maintains transport quality
Colour and pigment	Lycopene content	80–20 mg/ kg FW	Enhance colour intensity	Deep red colour desired by industry
	Beta-carotene	Moderate	Balanced nutritional quality	Influences colour hue and health benefits
	Uniform ripening gene (u/u)	Stable uniform red colour	Avoid blotchy ripening	Improves grading and consumer appeal
Physico-chemical traits	Total soluble solids (TSS)	6–8 °Brix (fresh fruit)	Reduce evaporation time	High solids = lower processing cost
	Titratable acidity	0.30–0.50% citric acid	Balanced flavour	Ideal for sauces and ketchup
	pH	< 4.4	Microbial safety	Avoids need for acidification
	Sugar–acid ratio	15:1 (high reducing sugars)	Improve flavour	Consumer preference
	Viscosity (pulp)	High viscosity; low Bostwick (4–6 cm)	Increase thickness	Required for paste/ketchup
Industrial / processing traits	Pulp percentage	≥ 65–75%	Maximize processed yield	Critical in paste factories
	Colour a*/b* ratio	> 2.0	Stable bright red colour	Used for premium paste and ketchup
	Consistency (Bostwick)	Paste: 4–6 cm; Ketchup: 7–10 cm	Improve product texture (Lower = thicker, premium grade)	Standard industry measurement
	Peelability	Easy peel (hot/cold)	Reduce processing loss	Essential for canned/whole tomatoes
	Concentration ability	High	Efficient evaporation	Saves energy cost
	Dry matter	≥ 6–8%	Higher TSS and viscosity	Key for pulp/paste industries
Agronomic and stress traits	Yield potential	≥ 50–70 t/ha	Ensure economic returns	Needed for industrial supply
	Heat tolerance	High	Maintain quality under stress	Processing zones often face high temp
	Disease resistance	ToLCV, BW, EB, PM, CMV	Stable fruit quality	Avoids yield fluctuations
	Shelf life	48–72 hours post-harvest	Allow transport to processing plants	Especially important in India
Genetic traits and molecular targets	High-Brix genes/ QTL	Brix9-2-5, Lin5, Sugar-enhancing alleles	Increase °Brix naturally	Reduces energy cost in factories
	Colour QTL/ genes	RIN, nor, hp-1, ogc	Enhanced lycopene & uniform red	Used in colour-intensive products
	Firmness genes	PG, Expansin, ACO, ACS mutants	Improve shelf-life & firmness	Essential for mechanical harvesting
	Viscosity QTL	fw2.4, pectate lyase regions	Improve paste viscosity	Key trait for ketchup
	Disease-resistance genes	Ty series, Mi-1, Pto, I2, Ve, Ph3	Durable resistance	Lower pesticide residues in processed foods

Total soluble solids (TSS): The most important economic parameter in tomato processing is total soluble solids (TSS), which is composed of approximately 65–75% sugars (primarily fructose and glucose), 8–15% organic acids, and smaller fractions of amino acids, pectins, minerals, and phenols (Portugal *et al.,* 2015). The processing industry requires at least 5.0–5.5 °Brix for industrial use (Tiwari *et al.,* 2023). The higher the TSS content, the more efficient the process is due to high recovery of the product and less energy/time spent on concentration. Higher °Brix values also improve processing efficiency by reducing water evaporation during paste production, resulting in increased industrial yield and profitability. In other words, an increase of 1% in TSS content leads to high recovery of the processed product and less need for raw materials by 25% to produce 28% tomato sauce (Portugal *et al.,* 2015).

Fig. 2: Tomato genotypes with special horticultural traits

Acidity (pH and titratable acidity):The acidity of tomatoes is essential not only from the point of view of the consumer qualities of the vegetable but also from the perspective of its shelf-life safety. The food industry needs to use varieties with inherent acidity below 4.4 (Tiwari *et al.,* 2026). Generally, tomatoes are classified as high-acid fruits; however, keeping acidity lower than 4.45 is a must from an industrial point of view in order to minimize the activity of spoilage microorganisms, namely, Bacillus coagulans, and thus the intensity of heat treatment required in canning (Chattopadhyay *et al.,* 2013). Titratable Acidity (TA): Titratable acidity (TA) plays an important role in the process of food manufacture since higher titratable acidity enables the adjustment of thermal treatment period in the process of sterilization that provides energy saving (Vieira *et al.,* 2020). The most important attributes determining consumer acceptance of the foodstuff include its sweetness, sourness, and tartness, which mainly depend on the sugar/acid ratio. Although citric acid remains the dominating acid in terms of TA contribution, malic and glutamic acids should also be mentioned. On the contrary, over maturity results in the decreasing of total TA whereas glutamic acid increases ten times (Anthon *et al.,* 2011).

Lycopene content:The carotenoid responsible for the red colour of tomatoes is called lycopene, and this 40 carbon atom isoprenoid is known to have 11 double bonds and be a very effective antioxidant (Alda *et al.,* 2009; Arballo *et al.,* 2021). It makes tomatoes look red and provides their strong health properties by reducing the likelihood of suffering from cardiovascular disease or prostate cancer (Vats *et al.,* 2020). From the point of view of processing, lycopene level in tomatoes remains unchanged and can even increase under such conditions. Carotenoids accumulate while processing takes place; for instance, the number of carotenoids rises from 6.74 mg/100 g in fresh tomato juice up to 34.31 mg/100 g of tomato paste (Kamil *et al.,* 2011). From the point of view of industrial use, a desirable amount of lycopene would be between 10–14 mg/100 g of fresh tomatoes, along with a high colour value (a/b ratio above 2.0) to achieve a proper red colour (Chattopadhyay *et al.,* 2013). Heat processing converts lycopene to its cis form and enhances its bioavailability relative to raw tomatoes.

Sugars and organic acids:The taste of tomato products is dependent upon the ratio of soluble sugars to organic acids. An ideal sugar-to-acid ratio should be about 15:1, as it ensures the product is neither too sour nor too sweet. In domesticating tomatoes, the process of breeding has centered on ensuring an appropriate malate and citrate ratio (Chattopadhyay *et al.,* 2013; Sadashiva *et al.,* 2022). Glucose and fructose sugars, along with organic acids such as citric acid and malic acid, contribute to the taste profile, including sweetness and sourness (Beckles, 2012). Also, glutamic acid content has been known to increase by ten times in concentration as tomatoes ripen, interacting with 5′-AMP to provide the umami taste (Oruna Concha *et al.,* 2007; Anthon *et al.,* 2011).

Pectin and cell wall components:Viscosity and textural properties of tomato products such as tomato paste and ketchup rely heavily on the structural stability of their cell walls, which consist mainly of pectic polysaccharides, hemicellulose, and cellulose (Steele *et al.,* 1997; Barrett *et al.,* 1998). As tomato fruits mature, the enzymes PG and PME degrade pectic compounds, causing cell separation and the fruits' softening (van Dijk *et al.,* 2006; Wang *et al.,* 2018). Temperature during processing can affect the function of these enzymes. When the hot break technique (≥85 °C) is employed, both PG and PME get deactivated instantly, yielding a highly viscous product. On the other hand, when using the cold break technique (~60 °C), PG and PME retain some enzymatic activity, generating a product that is less viscous but more flavoursome (Sánchez *et al.,* 2002). Ideally, when tomato products are being made, a natural juice viscosity level of 12–14 Bostwick cm/30 sec is recommended (Sadashiva *et al.,* 2022).

Volatile compounds:Aroma and flavour attributes of tomato products are attributed primarily to volatile organic compounds (VOCs), which make up only small concentrations but still are significant in sensory evaluation (Goff and Klee, 2006). In spite of the fact that over 400 different VOCs are found in tomatoes, only 30 VOCs occur at concentrations high enough to be able to influence taste (Baldwin *et al.,* 2000; Distefano *et al.,* 2022). These VOCs can be synthesized through metabolic processes associated with amino acids, lipids, phenolics, and carotenoids. The key volatiles hexanal, cis-3-hexenal, linalool, and apocarotenoids work together with sugars and organic acids to create the typical taste of tomatoes (Klee and Tieman, 2013; 2018). The aroma is due to the interaction of all these volatiles and other dissolved components, forming the sensory profile of tomato-based foods (Tieman *et al.,* 2012).

Physiological traits

Tomato plant physiology is crucial for assessing growth potential, adaptability, and fruit quality. With regard to processed tomatoes, physiological efficiency with respect to ripening performance, cell stability, carbon allocation, and stress tolerance greatly affects yield and recovery rates (Nie *et al.,* 2024).

Fruit ripening behavior

Uniform ripening (Concentrated Fruit Maturity) (CFM): Concentrated ripeness (uniform ripening) is one of the desirable characteristics in processing tomatoes. Being climacteric fruits, the respiration rate increases when tomato fruits ripen. The even colouration in tomato fruits is essential for both marketability and processing purposes (Nunes, 2009; Yahia and Brecht, 2012). Tomato fruits need to uniformly turn from orange to deep red colour without the presence of any green shoulders or patches. In actual situations, fruits that have matured to the green stage are exposed to ethylene treatment to encourage uniform ripening (Kandasamy, 2022). For processing types, tomato fruits are chosen because of their uniform maturity to ensure that most fruits attain their required colour and soluble solids content at the same time, which makes harvesting easier.

Ethylene regulation: Ethylene (C_2H_4) is another important phytohormone that plays an essential role in tomato development, ripening, and senescence. Therefore, its regulation is necessary during postharvest treatment. Variations in ethylene levels can impact the shelf-life of fruits, since storage conditions such as heat above 38 °C and cold temperatures could limit its production. Molecules such as 1-methylcyclopropene (1-MCP) help to control fruit ripening through the binding of ethylene receptors, thus lowering the activity of enzymes, including ACC synthase and ACC oxidase (Khan and Singh, 2009). On a molecular basis, ripening is associated with higher levels of expression of genes responsible for the biosynthesis of ethylene, for example, the Le-ACO1 gene, leading to the degradation of chlorophyll and activating genes encoding carotenoids biosynthesis, such as *Psy1*, causing lycopene accumulation (Yin *et al.,* 2010; Li *et al.,* 2018, 2020).

Shelf-life and textural integrity

Delayed softening: Being rigid and increasing shelf-life after harvest is important in minimizing mechanical injury that occurs during transportation since fruit softening is a consequence of degradation of cell wall constituents such as pectin and hemicellulose through enzymatic activities (Wann, 1996). Enzymes responsible for this include PG (polygalacturonase), pectinases, β-galactosidases and expansins. Several options can be considered to help slow down fruit softening and improve their qualities. One is genetic engineering where, for instance, PL gene is silenced, which leads to increased rigidity without changing other qualities such as yield, colour and soluble solid contents (Uluisik *et al.,* 2016). Alternatively, there are physiological and postharvest methods such as precooling, application of 1-MCP (1-methylcyclopropene), ultrasonic treatment or thermosonication**.**

Resistance to physiological disorders: Prevention of early decay in tomatoes demands genetic and physiological regulation. Genetically induced mutations like *rin* (ripening inhibitor), *nor* (non-ripening) and *alc* (alcobaca) have been extensively used in tomato breeding programs to inhibit softening and prolong shelf life due to additive and epistatic interactions (Rothan *et al.,* 2019; Wang *et al.,* 2020). Like most fruits, tomatoes also suffer from chilling sensitivity. It occurs when fruits are exposed to temperatures lower than 12–13 °C, causing poor colour distribution, development of surface pitting, seed darkening and off-flavour formation in tomatoes (Biswas *et al.,* 2016). Chilling resistance can be induced in tomato fruits by heat preconditioning before storage by dipping tomatoes into hot water at 42 °C or hot air, thus increasing the level of antioxidants (Yahia *et al.,* 2007).

Photosynthate partitioning and source-sink dynamics

Source-sink relationship: Dry matter and soluble solid contents in tomatoes are controlled by source-sink interactions in which the assimilates generated in mature leaves (sources) are transferred to immature fruits (sinks). In development, the fruit serves as an important sink for carbohydrates for respiratory and energetic purposes (Saltveit, 2019). Post-harvesting, the availability of nutrients ceases, and the fruit relies solely on internal stores. As the stores are progressively consumed due to respiration, the fruit ages and deteriorates (Nunes, 2009). For tomatoes, the sugar content is governed by assimilate transport, accounting for almost 80% of the sugars derived from mature leaves (Khapte *et al.,* 2019). This determines the total amount of soluble solids. In addition to that, gluconeogenesis plays a role during fruit ripening by stimulating the expression of the phosphoenolpyruvate carboxykinase (PEPCK) gene, increasing sugars and organic acids (Yin *et al.,* 2010).

Fresh tomatoes have 5-7.5% dry weight content. Most of the dry matter consists of sugars, specifically fructose, glucose, and sucrose, which impart sweetness (Hou *et al.,* 2020). The maximum content of starch is attained during the mature green stage and then becomes transformed into simple sugars as the fruits continue to ripe (Zhu *et al.,* 2022). The composition of sugar within the fruit may differ depending on the parts of the fruit as well, with more simple sugars present in seeds than locular tissues and less amount of organic acids, thus impacting its taste. Environmental factors such as heat may impact assimilate translocation to fruits hence decreasing their weight and soluble solids content (Plaut *et al.,* 2004).

Stress tolerance and quality stability

Heat, drought, and disease tolerance: Tomatoes grown using open-field techniques suffer from different types of environmental stresses. Current strategies including CRISPR/Cas9 have demonstrated their effectiveness in enhancing stress tolerance (Ahmad *et al.,* 2018). Heat stress (temperatures exceeding 32 °C) is highly detrimental, as it impacts pollen viability, pollen tube growth, and stigma functionality, thereby causing flower abortion and yield loss (Peet *et al.,* 1998; Alsamir *et al.,* 2021). Besides, it also negatively impacts the photosynthetic process by limiting the function of enzymes such as Rubisco activase and decreasing lycopene synthesis (Wahid *et al.,* 2007).

At a genetic level, *BZR1* gene expression responds to elevated temperatures via the Feronia (FER) pathway, whereas *CBF1* gene is responsible for defending tomato against cold stress through electrolyte leakage prevention (Yin *et al.,* 2018; Yun *et al.,* 2022). On the other hand, under drought stress, *MAPK3* gene assists in maintaining the integrity of the cell membrane and stress resistance (Huang *et al.,* 2023). Physiologically, water management techniques such as regulated deficit irrigation (RDI) and partial root-zone drying (PRD) minimize vegetative growth and promote assimilate partitioning, eventually enhancing total soluble solids without significant yield penalties (Khapte *et al.,* 2019). Genetics can also be used to enhance resistance to disease. For instance, altering the *JAZ2* gene will lead to resistance to bacterial speck resulting from infection by *Pseudomonas syringae* (Ortigosa *et al.,* 2019). Modifying genes that increase susceptibility to pathogens like *DMR6, PMR4* and *Mlo1* may also confer resistance to diseases caused by fungi. Resistance to viruses may be conferred by targeting viral sequences and plant defences, including *DCL2* that confers resistance to tomato yellow leaf curl virus and other RNA viruses (Tashkandi *et al.,* 2018; Zhang *et al.,* 2024).

Important for stable processing quality: To sustain stability in the process of tomato production, there is a need for good management of the biotic stress factors as well as pre- and post-harvest factors. The occurrence of quality losses such as early softening and decay results in considerable financial losses (Thole *et al.,* 2020). Some of the organisms that cause post-harvest losses include Erwinia, Alternaria, Botrytis, and Aspergillus (Youssef *et al.,* 2022). Through genetic methods involving control of ethylene formation, extending shelf-life, and improving disease resistance, losses during storage and transportation can be reduced (Shipman *et al.,* 2021). Genes like *Ve1* for Verticillium wilt and *Bs2* for bacterial spots also play an important role in maintaining good health and consistency of produce (Chaudhary *et al.,* 2019). The quality of the fruit's processing depends on its metabolism as well. Abiotic stress in moderate quantities like salinity and heat leads to an increase in the amount of sugar, amino acids, and antioxidants like ascorbate, carotenoids, and flavonoids, thus improving the quality of the fruit and making it more nutritious without significantly reducing the yield (Massaretto *et al.,* 2018; Egea *et al.,* 2022). Gene expression regulation related to shelf life and stress tolerance improves the quality of the products and their availability for processing (Cappetta *et al.,* 2021).

Molecular and genomic aspects

Progress made in classical genetics and novel genomic approaches has significantly enhanced breeding programs in tomato. The presence of a reference genome of approximately 900 Mb size with 34,700 protein-coding genes makes tomato an attractive model plant for the study of processes of fruit development and tolerance to abiotic stresses (Tomato Genome Consortium, 2012). Innovative methods of functional genomics, transcriptomics, and gene editing provide the possibility of thorough analysis of processing quality-related traits (Ranjan *et al.,* 2012). Processing traits and genes for tomato breeding are summarised below in Table 3. Besides other traits are thick pericarp, fruit firmness, small locule, small core, no radial and concentric cracking, elongated, smooth surface/ free from wrinkles, high viscosity (consistency), high alcohol-insoluble solids, high yield, resistance to diseases like tomato leaf curl virus (ToLCV), bacterial wilt, early blight and late blight.

Table 3: Processing traits and genes for tomato breeding

Trait	Gene
Determinate/ self-pruning	*sp*
Concentrated fruit maturity	*cfm*
Jointless	*j-2*
Uniform ripening	*u*
Single flower truss	*SFT*
Sucrose accumulator (for high TSS)	*sucr*
Old gold crimson	og^c
Intense pigment (deep red)	*Ip*
High pigment-2 (high lyconene)	*hp-2*

Key genes in tomato processing traits

RIN (Ripening-inhibitor): The RIPENING INHIBITOR (RIN) gene encodes a MADS-box transcription factor that acts as a key regulator of climacteric fruit ripening (Vrebalov *et al.,* 2002). It modulates the expression of genes associated with ethylene biosynthesis, carotenoid accumulation, and cell wall modification (Martel *et al.,* 2011; Li *et al.,* 2018). The classical *rin* mutation (LeMADS-RIN) delays ripening and extends shelf life in F_1 hybrids, leading to reduced lycopene accumulation, impaired softening, and downregulation of ripening-associated genes; the absence of a climacteric ethylene peak primarily reflects transcriptional repression of key ethylene biosynthetic genes (Kitagawa *et al.,* 2005). Recent CRISPR/Cas9 studies further show that RIN is not essential for ripening initiation but is required for its proper progression, particularly for inducing the system-2 ethylene burst necessary for full colour and flavour development (Li *et al.,* 2020). Furthermore, RIN has been implicated in preventing excessive fruit softening (Ito *et al.,* 2020), and its activity is enhanced through interaction with the SnRK1 kinase, which promotes the expression of ripening-associated genes (Yu *et al.,* 2018). These findings indicate that RIN plays an important role in coordinating hormonal, transcriptional and metabolic processes involved in climacteric fruit ripening.

PG and PL (Cell Wall Softening): Firmness of fruits and thickness of pastes mainly depend on how much pectin breaks down. This breakdown relies on enzymes like polygalacturonase (PG) and pectate lyase (PL). Blocking PL activity increases fruit firmness and helps keep cell walls intact, without harming other important qualities like total soluble solids and colour (Uluisik *et al.,* 2016). Processing methods affect enzyme activity. For example, high-pressure and heat treatments can deactivate key enzymes, but they each have different levels of resistance. Polygalacturonase can be deactivated even at moderate temperatures. In contrast, pectin methylesterase is more resistant, so it requires a carefully adjusted approach using these methods (Crelier *et al.,* 2001). Additionally, different types of PG respond differently to temperature and high-pressure treatments, while pectin methylesterase remains stable (Rodrigo *et al.,* 2006). Processing methods can also improve product quality by reducing off-flavours through enzyme inactivation, such as lipoxygenase and PG, while maintaining texture (Shook *et al.,* 2001). At the molecular level, silencing certain genes, like SlPL and SlPL16, can manage cell wall metabolism to improve firmness and extend shelf life (Yang *et al.,* 2017, 2021; Ren *et al.,* 2023).

Genome editing and Marker-Assisted Selection (MAS)

Marker-assisted selection (MAS) has advanced the development of processing tomato cultivars through increased efficiency in the breeding of complex traits while reducing the need for extensive phenotyping and linkage drag (Foolad and Panthee, 2012). A few genes/ QTLs associated with processing traits in tomato are outlined in Table 4. In parallel, CRISPR/Cas9- based genome editing has emerged as a powerful tool for precise trait improvement. For instance knockout of *SlINVINH1* and *SlVPE5* using CRISPR/Cas9 resulted

Table 4: Genes/QTLs associated with processing traits in tomato

Trait	Gene / QTL	Chr	Marker / position	Function
TSS (°Brix)				
TSS	*Lin5 (cell wall invertase) (Brix9-2-5)*	9	SSRs, SNPs near 9:4–6 Mb	Sucrose hydrolysis (Suc → Glc + Fru); major TSS regulator
TSS	*Solyc09g010080 (Lin5)*	9	SNPs	Sugar metabolism
Glucose–fructose ratio	*gfa*	9	Linked with *Lin5*	Sugar partitioning (Fru↑)
TSS	*TSS1.1 (QTL)*	1	1:20–55 Mb	Minor sugar modifier
TSS	*TSS9.1 (QTL)*	9	9:3–7 Mb (*Lin5* region)	Major TSS QTL
Fruit sweetness	*SUT1 (Solyc03g007150)*	3	SNP linked to SUT1	Sucrose transporter from phloem to fruit
TSS	*SUT2 (SUC2 family)*	9	Near 9:60–65 Mb	Long-distance sucrose unloading
Sugar accumulation	*TIV (Tomato Invertase-Vacuum)*	6	6:30–40 Mb	Cell wall/ vacuolar invertase activity
Soluble sugars	*TST1 / TST2 (Tonoplast sugar transporters)*	4 / 11	SNP regions 4:5–8 Mb, 11:45–48 Mb	Vacuolar sugar loading
TSS	*FUL1/ FUL2 (Fruit ripening regulators)*	6 / 11	QTL peaks linked to FUL1-FUL2	Regulate cell expansion and sugar influx
TSS	*fw2.2-associated sugar QTL*	2	2:45–60 Mb	Small fruit → higher concentration
Fruit quality index	*GAD2 (γ-aminobutyrate decarboxylase)*	10	SNP in 10:4–7 Mb	Alters carbon flux → sugars
TSS	*Hexokinase (HXK1)*	2	QTL co-localized	Sugar sensing and metabolism
Sugar content	*Sucrose phosphate synthase (SPS)*	8	8:2–4 Mb	Controls sucrose synthesis
Sugar retention	*Alba1 (cuticle thickness)*	11	11:50–52 Mb	Lower water loss → ↑ TSS
Acidity / titratable acidity (TA) and pH				
TA (malate)	*ALMT9 (Aluminum-activated malate transporter)*	4	SNP near gene *Solyc04g005080*	Vacuolar malate uptake → ↑ acidity
TA (malate)	*NAD-ME (Solyc06g072910)*	6	SNP region	Malate decarboxylation and metabolism
TA	*TA2.1 (QTL)*	2	SSR/SNP cluster	Organic acid biosynthesis regulation
Fruit pH	*PH3 (proton homeostasis gene)*	3	SNP associated	Regulates H^+ pumping and apoplastic acidification
TA (citrate)	*Solyc03g083130 (CS – Citrate synthase)*	3	Linked SNP in 3:63–67 Mb	Citrate accumulation at early ripening
TA (citrate)	*ACO1 (Aconitase)*	12	QTL-linked SNP	Converts citrate → isocitrate; ↓ TA
TA (total acids)	*mdh (Malate dehydrogenase)*	10	SNP/QTL co-localized	Malate ↔ OAA equilibrium
Acidity and flavour	*V-ATPase subunit A/B*	11 / 9	Candidate SNP peaks	Vacuolar acidification, fruit sourness perception
Fruit pH / TA	*SLNR (Nitrate reductase regulatory)*	6	Linked in 6:40–55 Mb	Nitrate assimilation influences acid flux
Organic acids	*GA2ox1*	2	SNP in TA2 QTL	Hormonal effects → fruit size vs. acid dilution
Fruit firmness				
Firmness	*PG2A (Polygalacturonase)*	10	TfmA, PG-linked SNPs	Pectin degradation; major softening enzyme
Firmness	*PL (Pectate lyase; Solyc08g062490)*	8	SNP associated	Pectate cleavage → reduced firmness
Firmness	*CEL2 (Cellulase)*	9	SNP near gene	Cell wall breakdown; softening rate
Firmness	*Firm3.1 (QTL)*	3	Major QTL peak	Texture regulation
Firmness / storage shelf -life	*RIN (Ripening-Inhibitor)*	5	5:3–5 Mb, SNPs & Indels	Master ripening transcription factor; delays softening
Firmness / delayed softening	*NOR (Non-ripening)*	10	Linked SNPs & Indels	Ethylene regulation of ripening and texture
Firmness	*EXP1 (Expansin 1)*	2	2:45–48 Mb QTL	Cell wall loosening, early softening
Firmness	*PME1 (Pectin Methylesterase)*	1	SNP cluster	Pectin modification → firmness retention
Cuticle-linked firmness	*CD2 (Cutin Deficient 2)*	11	11:50–53 Mb	Cuticle structure → reduces water loss
Fruit firmness and shelf-life	*LCY-E* (via cell wall-associated pathways)	11	SNP/QTL linked	Lycopene metabolism → correlates with firmness QTL
Firmness	*FIR2 (QTL)*	4	4:20–30 Mb	Texture stability

Trait	Gene / QTL	Chr	Marker / position	Function
Mechanical firmness	*JOINTLESS2*-associated *QTL*	12	12:42–46 Mb	Reduces abscission-related softening
Colour (lycopene, β-carotene, colour uniformity)				
Lycopene (red pigment)	*Psy1 (Phytoene synthase) (Solyc03g031860)*	3	SNPs / functional alleles	Rate-limiting carotenoid biosynthesis step
β-carotene (orange fruit)	*Beta (B) (Solyc06g074240)*	6	SNP markers	Converts lycopene → β-carotene (orange pigmentation)
Colour uniformity	*t (uniform ripening) (Solyc10g086180)*	10	SNP near Golden2-like gene	Chloroplast development in immature fruit; uneven ripening if recessive
Red colour formation	*r / r²*	3	Linked with *Psy1* region	Loss-of-function reduces red pigmentation
Lycopene	*LYC1.1 (QTL)*	1	SNP cluster	Minor lycopene contributor
Carotenoid stability	*CRTR-B1 (β-carotene hydroxylase)*	6	SNP close to B locus	Converts β-carotene → zeaxanthin; modulates β-carotene
Lycopene accumulation	*ZISO (Z-isomerase)*	2	SNP around 2:40–45 Mb	Enhances cis-carotenoid accumulation → ↑ lycopene
Carotenoid sequestration	*CHRC (Chromoplast protein)*	1	Co-localized QTL SNPs	Maintains lycopene crystals for red colour intensity
Ripening and colour	*RIN (Ripening-Inhibitor)*	5	SNP / Indel	Ripening TF increase lycopene; mutants cause pale fruit
Ethylene-linked colour	*NOR (Non-ripening)*	10	Marker-linked region	Controls carotenoid onset; non-ripening mutants: green-yellow fruit
High-pigment phenotype	*hp-1 / hp-2 (DDB1 / DET1)*	7 / 1	SNPs widely used in breeding	↑ Chloroplasts → ↑ lycopene, vitamin C, firmness
External / internal colour	*BIC1 / BIC2 (BLUE-LIGHT INHIBITOR genes)*	3 / 11	SNP/Indel	Carotenoid precursor regulation by light response
Viscosity and processing recovery				
Viscosity / pectin strength	*PE1 (Pectinesterase / PME)*	1	SNP linked	Pectin de-esterification → ↑ cell wall rigidity and viscosity
Viscosity / cell wall integrity	*XTH (Xyloglucan endotransglycosylase)*	3	SNP near candidate locus	Xyloglucan modification → pulp consistency
Major viscosity QTL	*QTL-Visc9.1*	9	RFLP / SNP cluster	Controls pulp thickness and serum viscosity
Serum viscosity	*QTL-Visc5.2*	5	SNP region	Water/juice separation regulation
Pulp thickness and yield	*fw11.3-associated QTL*	11	11:48–52 Mb	Thick pericarp → ↑ viscosity
Processing consistency	*VGT QTL* (viscosity and firmness related)	2	SNP peaks co-localized with firmness loci	Coordinated control of pectin retention
Pectin biosynthesis	*GAUT family (Galacturonosyltransferases)*	4	New GWAS SNP hits	Homogalacturonan synthesis → improves viscosity
Fruit size				
Fruit size (major QTL)	*fw2.2*	2	SNP interval 2:44–46 Mb	Regulates carpel cell division; negative growth regulator
Fruit size	*fw3.2 (Cytochrome P450 family)*	3	QTL region 3:60–70 Mb	Regulates pericarp cell proliferation
Locule number	*lc (locule number)*	2	Near WUSCHEL response element	Controls carpel primordia → ↑ locules
Fruit size and locule number	*fas (fasciated)* (YABBY transcription factor)	11	SNP near Solyc11g071840	Floral meristem development; increases locules → large fruit
Fruit weight and shape	*fw11.3*	11	QTL peak	Pericarp thickening and weight gain
Fruit weight / introgressed trait	*SUN*	7	7:60–65 Mb	Horizontal elongation; increased weight
Shape and size	*OVATE*	2	2:25–28 Mb	Controls pear/elongated shapes; weight effects
Locule number	*QTL-loc5.1*	5	QTL region	Minor contributor to locule variation
Fruit size	*CSR/QTL-FW9.1*	9	SNP cluster	Cell expansion in pericarp
Pericarp development	*SlKLUH (CYP78A5)*	1	SL4.0 SNP hits	Organ size expansion → ↑ fruit weight
Ascorbic acid (vitamin C)				
Ascorbic acid biosynthesis	*GME (GDP-mannose epimerase)*	9	SNP linked to *Solyc09g008900*	GDP-mannose → L-galactose pathway precursor

Trait	Gene / QTL	Chr	Marker / position	Function
Ascorbic acid biosynthesis (final step)	*GLDH (L-galactono-1,4-lactone dehydrogenase)*	9	SNP region	Catalyzes final step of AsA biosynthesis in mitochondria
Ascorbic acid QTL	*QTL-AsA8.1*	8	SNP cluster	Variation in total AsA concentration
Recycling of AsA	*MDHAR (Monodehydroascorbate reductase)*	6	Putative SNP peak	Regenerates AsA from oxidized form → ↑ antioxidant content
Ascorbate–glutathione cycle	*APX (Ascorbate peroxidase)*	4	Candidate SNP	Detoxifies ROS; maintains reduced AsA pool
High-pigment antioxidant boost	*hp-1 / hp-2 (DET1 / DDB1)*	1 / 7	Indels/SNPs	↑ Chloroplast development → ↑ AsA + lycopene
Stress-linked Vit-C QTL	*QTL-AsA3.2*	3	QTL-linked markers	UV and stress-induced AsA accumulation
Minor AsA contributor	*PMI (Phosphomannose isomerase)*	5	GWAS SNP hits	Regulates hexose flux into AsA pathway
Jointless trait (mechanical harvesting)				
Jointless pedicel	*J (Solyc11g010570)*	11	SNP, CAPS markers (11:0–2 Mb)	MADS-box gene controlling abscission zone formation
Improved jointless	*j-2 (Jointless-2) (Solyc12g038510)*	12	SNP markers	Jointless phenotype without deleterious inflorescence defects
Jointless QTL Complex	*J–comp / ej2*	11 and 12	Linked QTL blocks	Epistasis between J and ej2 stabilizes jointless trait

in the accumulation of more sugars, including glucose, fructose, and total soluble solids (TSS) in tomato fruits, and a double knockout had a synergistic effect with higher sugar accumulation than single gene knockouts, which may be a potential strategy to increase fruit sweetness and processing quality (Wang *et al.,* 2021).

Furthermore, CRISPR/Cas9 has been used to increase the fruit's lycopene content by stimulating its biosynthesis and repressing conversion to other forms of carotenoid, thereby improving the nutritional properties of the fruit (Li *et al.,* 2018). Studies conducted on transcriptomics have shown that genes related to the activity of pectinases, such as pectate lyase (PL) and pectin methyl esterase (PME), play an important role in fruit development due to cell wall remodelling processes (Wen *et al.,* 2025). The MAS technique is useful in early screening for various desirable traits like better fruit colour, increased levels of lycopene and resistance to root-knot nematodes (Kumar *et al.,* 2023). Moreover, techniques like genome resequencing, pan-genomics, SNP genotyping, GWAS and GS have also helped in identifying significant genes and markers, making the process more efficient (Tiwari *et al.,* 2022). In summary, the CRISPR/Cas9-mediated targeted genome editing of genes related to soluble sugar accumulation or carotenoid metabolism is a highly effective strategy for enhancing sweetness and lycopene content in fruit, with stable, heritable effects over multiple generations (Li *et al.,* 2018; Wang *et al.,* 2021).

CONCLUSION

The improvement in tomato for processing quality requires a holistic integration of morphological, biochemical, physiological, and molecular traits. Processing efficiency and product quality are largely governed by attributes such as high TSS, balanced acidity, enhanced lycopene content, firm texture, and desirable fruit architecture, all of which are controlled by complex genetic mechanisms and influenced by environmental factors. Traditional breeding approaches, although valuable, are insufficient to address the polygenic nature of these traits and the challenges posed by climate variability and yield quality trade-offs. Recent advancements in genomics, including QTL mapping, GWAS, marker-assisted selection, and CRISPR/Cas9-mediated genome editing, have provided precise tools for targeted improvement of processing traits. Identification of key genes such as *RIN*, *LIN5*, *hp-2*, and those involved in cell wall metabolism and sugar transport has enabled more efficient breeding strategies. Furthermore, utilization of wild relatives and genomic selection approaches offers opportunities to broaden the genetic base and enhance stress tolerance. For countries like India, strengthening dedicated processing tomato breeding programs, fostering public–private partnerships, and improving value chain linkages are critical for expanding the processing industry. Future breeding efforts should focus on developing high-yielding, climate-resilient cultivars with superior processing quality tailored to industrial requirements. The convergence of conventional and modern breeding approaches will be pivotal in achieving sustainable growth and global competitiveness in the tomato processing sector.

ACKNOWLEDGMENTS

Research was supported by the Indian Council of Agricultural Research, Department of Agricultural

Research and Education, Government of India. We thank the Competent Authority of ICAR-IIVR, Varanasi, for support.

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Current Horticulture 14(3): 19-24, July–September 2026
DOI: 10.5958/2455-7560.2026.00033.6
Received: 24 June 2026; Revised: 16 July 2026: Accepted: 03 September 2026

Research Review Article

Enhancing nutrient-use efficiency and productivity in tomato (*Solanum lycopersicum*) using blended fertilizers: a review

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Abstract

Tomato (*Solanum lycopersicum* L.) is a globally vital vegetable crop, yet optimizing its genetic potential for yield and quality is frequently hindered by suboptimal soil fertility management. Continuous blanket application of straight macronutrient fertilizers often results in imbalanced plant nutrition by contributing to secondary and micronutrient deficiencies.Multi-nutrient blended fertilizers incorporating primary, secondary, and micronutrients have emerged as a critical innovation to deliver a balanced nutrient profile. However, a comprehensive synthesis of their interactive mechanisms, optimal formulations, and agro-ecological performance remains fragmented. A systematic narrative review framework was executed by querying dominant digital databases (including Web of Science, Scopus, Science Direct, and Google Scholar) for peer-reviewed field, greenhouse, and meta-analysis studies spanning from 2000 through mid-2026. Information on tomato growth, yield components, nutrient use efficiency indices, and environmental impacts was extracted and synthesized qualitatively. The synthesized literature reveals that tailored multi-nutrient blends systematically resolve physiological bottlenecks, expanding leaf area index by 18% to 34% over conventional inputs. By optimizing floral development, reducing fruit abortion rates via boron (B) synergies, and mitigating blossom end rot through calcium (Ca) interactions, multi-nutrient blending drives absolute marketable fruit yield increases ranging from 15% to 42%. Furthermore, balanced fertilization promotes enhanced lateral root architecture and enhances root nutrient uptake through improved root growth and physiological activity, elevating agronomic and recovery efficiency while reducing nitrous oxide (N2O emissions and leaching. Transitioning to multi-nutrient blending technologies is a highly viable strategy to simultaneously maximize tomato productivity, improve human dietary health through trace element bio fortification, and reduce environmental footprints. Future research should prioritize long-term soil residual chemistry, nano-formulations, and targeted organo-mineral combinations.

Key words: Balanced nutrition, Micronutrient enrichment, Marketable yield, Nutrient uptake.

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and economically important vegetable crops globally, serving as a vital source of vitamins, minerals, and essential antioxidants like lycopene (Buajaila *et al.,* 2022; Gao *et al.,* 2023). Despite its high market demand and dietary significance, realizing the genetic yield and quality potential of tomato remains a major challenge for growers. A primary limiting factor is suboptimal soil fertility management. Traditionally, blanket applications of straight, highly soluble chemical fertilizers—primarily nitrogen (N), phosphorus (P), and potassium (K) have been the standard practice in intensive agriculture (Gao *et al.,* 2023). However, this imbalanced fertilization strategy often fails to match crop nutrient demand in terms of timing and quantity. (Rahman *et al.,* 2021). Over time, it leads to severe secondary and micronutrient deficiencies, accelerated soil degradation, and sharply declining nutrient use efficiency (NUE) due to substantial nutrient losses via leaching, volatilization, or environmental fixed-states (Gao *et al.,* 2023; Rahman *et al.,* 2021).

In response to these soil constraints, multi-nutrient blended fertilizers have emerged as a pivotal innovation in modern sustainable agriculture. By combining primary (N, P, K), secondary (such as sulfur, calcium, and magnesium), and micronutrients (such as boron, zinc, copper, and iron) into a single formulation, these blends aim to deliver a balanced, synchronous nutrient profile tailored to specific crop requirements and soil types (Jing, 2025; Stoeva, 2026). Balanced nutrition is well-documented to stimulate robust vegetative growth, increase plant height and leaf area index, enhance photosynthetic pigment synthesis, and improve yield components in tomatoes (Jing, 2025; Rahman *et al.,* 2021). Furthermore, synchronizing multi-element delivery minimizes internal plant nutrient antagonism and improves overall root uptake capacity, which significantly elevates the partial productivity of fertilizers and boosts long-term NUE (Liu *et al.,* 2024; White and Broadley, 2009).

The Knowledge Gap: While the broad agronomic benefits of macronutrient application are well-established, there is a critical shortage of synthesized data regarding how complex multi-nutrient blended formulations interact under varying agro-ecological conditions to influence the distinct physiological growth stages and overall fruit quality of *Solanum lycopersicum* L. (Gao *et al.,* 2023; Jing, 2025). Most existing literature focuses heavily on isolated, straight nutrient responses or localized

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organic-chemical combinations (Buajaila *et al.,* 2022; Gao *et al.,* 2023). This leaves the systematic synergistic mechanisms, optimal multi-element blending ratios, and the balancing point between micronutrient enrichment and potential yield reductions poorly understood and fragmented across the scientific community.

Consequently, a comprehensive synthesis of current research is urgently needed to guide future agronomic recommendations and custom fertilizer manufacturing. Therefore, the objective of this review is to evaluate the effects of multi-nutrient blended fertilizers on the growth parameters, yield attributes, and nutrient use efficiency of tomato (*Solanum lycopersicum* L.), highlighting current technical advancements, identifying critical research gaps, and outlining strategies for optimized, sustainable production.

Review approach

This study utilizes a systematic narrative review approach to evaluate, synthesize, and interpret existing scientific literature on the impacts of multi-nutrient blended fertilizers on agronomic performance of tomato. Rather than analyzing isolated nutrient elements, this approach allows for the integration of complex agronomic data across diverse soil profiles, macro-micronutrient blending formulations, and agro-ecological zones (Akinyemi *et al.,* 2023; Geremew *et al.,* 2026). By structuring the review process systematically, the analysis objectively traces the physiological mechanisms through which balanced formulations influence tomato vegetative growth, fruit yield components, and nutrient use efficiency (NUE) metrics, while thereby reducing potential reviewer bias (Gusenbauer and Haddaway, 2020; Snyder, 2019).

Search strategy

A comprehensive, multi-database digital search was executed to identify peer-reviewed research articles, book chapters, and technical reports published from January 2000 through June 2026. The primary electronic databases searched included Web of Science, Scopus, ScienceDirect, and Google Scholar (Gusenbauer and Haddaway, 2020; Tondey *et al.*, 2025). The search string was constructed using strict Boolean operators (and, or) and specific keyword truncations to capture all relevant publications.

The standardized search string applied across the engines was:

("tomato" or "*Solanum lycopersicum*") and ("multi-nutrient blend*" or "blended fertilizer*" or "balanced nutrition" or "micronutrient enrichment") and ("growth" or "yield" or "fruit quality" or "nutrient- use efficiency" or "NUE")

To minimize missing data, the reference lists of all retrieved primary studies and relevant global agronomic surveys were manually screened via backward snowballing to discover additional high-impact historical literature (Page *et al.,* 2021).

Inclusion and exclusion criteria

To maintain high scientific rigor and avoid confounding variables, clear inclusion and exclusion boundaries were established prior to screening the literature database (Higgins *et al.,* 2019; Tondey *et al.,* 2025).

Criteria	Inclusion boundaries	Exclusion boundaries
Study type	Peer-reviewed experimental studies, multi-year field trials, greenhouse/pot experiments, and meta-analyses (Akinyemi *et al.,* 2023).	Editorials, opinion pieces, non-peer-reviewed popular media, and studies lacking clear statistical validation or ANOVA indicators.
Crop focus	Tomato (*Solanum lycopersicum* L.) commercial varieties (field-grown, greenhouse, or hydroponic coir/ substrates).	Intercropping systems where tomato specific nutrient uptake data could not be isolated from the companion crop.
Intervention	Blended formulations combining primary macronutrients (NPK) explicitly with secondary (Ca, Mg, S) or micronutrients (Zn, B, Fe, Cu).	Studies evaluating *only* individual straight fertilizers (e.g., urea or triple superphosphate alone) without a multi-nutrient blending context.
Outcome measures	Quantifiable metrics for vegetative growth, fruit yield components, or calculated nutrient use efficiency (NUE) metrics (Geremew *et al.,* 2026).	Studies evaluating solely sensory preferences or post-harvest shipping engineering without active crop agronomic data.

Data extraction and organization

Articles meeting the inclusion criteria underwent a standardized data extraction process using a centralized matrix protocol to ensure alignment across datasets (Page *et al.,* 2021). The following parameters were systematically extracted from each text:

Bibliographic information: Author(s), publication year, and geographical location of the study.

Experimental metadata: Trial environment (field, greenhouse, or hydroponics), soil physicochemical properties (initial pH, organic matter, baseline nutrient status), and tomato cultivar type (indeterminated vs. determinated).

Fertilizer characteristics: Exact multi-element nutrient composition, blending ratios, total application rates (kg/ha), and timing or delivery methods (e.g., basal application vs. split top-dressing).

Agronomic target metrics: Vegetative data (plant height, leaf area index, dry biomass), yield data (fruit number per plant, average fruit weight, total marketable yield), and specific NUE indices, including agronomic efficiency (AE), apparent recovery efficiency (ARE), and partial factor productivity (PFP) (Fixen *et al.,* 2015; Geremew *et al.,* 2026).

Data synthesis and interpretation

Due to the heterogeneous nature of the collected agronomic data—stemming from varied soil conditions, differing nutrient blend concentrations, and divergent local environments—a qualitative and narrative data synthesis was executed (Snyder, 2019). Data were grouped categorically based on primary agronomic outcomes: growth response, total crop yield, and nutrient uptake dynamics.

The interpretation focused on identifying core physiological patterns, such as the synergistic interactions between macronutrients and micronutrients (e.g. how zinc or boron presence influences nitrogen or phosphorus uptake via enzyme activation) (Fixen *et al.,* 2015). Conflicting findings in the literature were systematically evaluated by cross-referencing environmental confounding factors, such as soil pH or irrigation regimes (Geremew *et al.,* 2026). Finally, the synthesized data were contrasted against traditional straight fertilizer baselines to quantify the net percentage variations in yield and NUE offered by modern multi-nutrient blending technologies.

Limitations of conventional nutrient regimes

Historically, soil fertility strategies for tomato (*Solanum lycopersicum* L.) cultivation relied heavily on conventional, straight macronutrient regimes—most notably Diammonium Phosphate (DAP) and Urea (Gao *et al.,* 2023; Hailu *et al.,* 2025). While this standard practice delivers concentrated inputs of nitrogen (N) and phosphorus (P), decades of continuous application have has contributed to several agronomic constraints.

Conventional methods ignore the depletion of secondary macronutrients and critical micro-elements. This imbalance leads to widespread “hidden hunger” in intensive vegetable systems (Fisseha *et al.,* 2026; Mashamaite *et al.,* 2024). Furthermore, highly soluble straight fertilizers saturate the soil solution rapidly, exceeding the immediate uptake capacity of the tomato plant’s roots. This lack of synchronization triggers major nutrient loss pathways:

- Free nitrates (NO_3) leach quickly past the root zone.
- Ammonium (NH_4) undergoes rapid volatilization.
- Soluble orthophosphates (H_2PO_4) bind tightly to iron and aluminum oxides in acidic soils, locking them in an unavailable, fixed state (Fixen *et al.,* 2015; Wu *et al.,* 2024).

Consequently, conventional fertilization often results in diminishing returns, poor fruit quality, and low nutrient use efficiency (NUE).

Emergence of blended NPSBZn formulations

To resolve the limitations of traditional macro-only protocols, recent research has increasingly focused on multi-nutrient macro-micronutrient complexes. A prominent innovation in this space is **NPSBZn** fertilizer—a targeted blend containing tailored proportions of Nitrogen, Phosphorus, Sulfur (S), Boron (B), and Zinc (Zn) (Fisseha *et al.,* 2026; Hailu *et al.,* 2025).

This multi-nutrient formulation acts as a comprehensive nutritional package. It addresses widespread trace element deficiencies caused by intensive farming and continuous soil mining (Fisseha *et al.,* 2026; Tondey *et al.,* 2025). In these micro-enriched blends, the individual nutrients are bound together, preventing the chemical segregation common in physical field mixes. This ensures uniform nutrient distribution across the crop field, giving every plant simultaneous access to all five elements (Hailu *et al.,* 2025).

Effect of NPSBZn on yield and its components

Extensive field trials demonstrate that shifting from conventional NPK or DAP/Urea baselines to blended NPSBZn fertilizer significantly increases total tomato productivity, typically optimizing application rates between 150 kg/ha and 250 kg/ha depending on the cultivar and local soil properties (Fisseha *et al.,* 2026; Hailu *et al.,* 2025). This yield bump is driven by the synergistic impacts of the blended components on individual yield attributes:

- **Flower retention and fruit set percentage:** Omiting boron in conventional systems causes high flower abortion rates. The inclusion of boron (B) within the NPSBZn matrix improves pollen tube elongation and grain viability. This directly reduces floral drop, resulting in a higher number of fruit clusters per plant and an increased overall fruit set percentage (Hailu *et al.,* 2025; Stoeva, 2026).
- **Fruit structural dimensions and marketable size:** Zinc (Zn) plays a key role as a catalytic building block for indole-3-acetic acid (IAA). This up-regulates cell division and expansion during early fruit development. When applied via balanced blends, zinc increases average fruit length, fruit diameter, and individual fruit weight (Fisseha *et al.,* 2026; Rahman *et al.,* 2021).

- **Reduction in unmarketable yield:** The combination of sulfur (S) with trace micronutrients improves the uptake of primary macronutrients and secondary elements like calcium (Ca). This physiological balance lowers the incidence of blossom end rot and fruit cracking, increasing the volume of high-quality, marketable fruit (Gao *et al.,* 2023; Hailu *et al.,* 2025).

Recent field studies evaluating diverse tomato varieties (such as *Melka sholla*, *Gele lma*, and *Roma-VF*) show that optimizing NPSBZn blending strategies regularly produces high fruit yields, with top performances reaching 38.1 to 64.11 t/ha (Fisseha *et al.,* 2026; Research Gate, 2024). These results highlight the strong economic and agronomic value of replacing outdated, straight fertilizer inputs with balanced, crop-specific formulations.

Effect of multi-nutrient blended fertilizers on growth

The synthesis of reviewed literature consistently demonstrates that multi-nutrient blended fertilizers containing macro, secondary, and micronutrients prompt a significantly higher vegetative growth response in tomato compared to conventional straight fertilizers (e.g. urea or DAP alone). Key growth indicators such as plant height, leaf area index (LAI), and total dry biomass production showed uniform positive responses to balanced multi-nutrient inputs across varied trial environments (Geremew *et al.,* 2026; Jing, 2025).

The observed expansion in growth parameters is mechanically linked to the physiological synergies of balanced nutrition. While nitrogen serves as the structural foundation for amino acids and chlorophyll synthesis, its metabolic processing depends heavily on the presence of trace elements. For instance, zinc (Zn) serves as a catalytic precursor for tryptophan synthesis, which is the direct metabolic driver of the growth hormone indole-3-acetic acid (IAA). Additionally, boron (B) is structurally vital for cell wall pectin cross-linking, facilitating continuous cell division at apical meristems (Stoeva, 2026; White and Broadley, 2009).

When these micronutrients are omitted in imbalanced fertilization schemes, plants exhibit physiological bottlenecks, marked by stunted growth, fragile stems, and localized interveinal chlorosis. Recent meta-analyses confirm that integrating organic matrices—such as Black Soldier Fly (BSF) compost—with mineral multi-nutrient blends enhances biochemical mineralization, resulting in increased dry shoot biomass and raising the plant health index significantly above standard synthetic NPK inputs (Zaato, 2025). Synthesized data reveals that incorporating secondary elements like sulfur (S) alongside trace micronutrients expands tomato LAI by 18% to 34% compared to NPK-only controls, directly optimizing net carbon assimilation rates via increased light interception (Rahman *et al.,* 2021).

Yield and its components

Tomato fruit yield is a multi-component metric dictated by the number of flower clusters per plant, fruit set percentage, average fruit weight, and the overall ratio of marketable to unmarketable fruit. The literature shows that multi-nutrient blends significantly enhance these specific yield components, culminating in elevated total fruit yields per hectare (Buajaila *et al.,* 2022; Liu *et al.,* 2024).

The physiological mechanism behind this yield bump lies in the transition from vegetative to reproductive growth. As illustrated in the developmental stages above, fruit set and expansion require intense carbohydrate translocation from leaves to developing sinks. Boron plays an indispensable role in maintaining pollen grain viability and pollen tube elongation; when blended into baseline fertilizers, it decreases flower abortion rates and dramatically increases the total number of fruits set per individual vine (Stoeva, 2026). Furthermore, the inclusion of potassium (K) combined with calcium (Ca) in multi-nutrient blends minimizes the occurrence of blossom end rot—a physiological disorder stemming from localized calcium deficiencies during cell expansion—thereby driving up the marketable yield index (Gao *et al.,* 2023).

Recent field trials reveal that when macro-micronutrient complexes are blended with biochar or tailored bio-composts, tomato yield increases of up to 191.6% can be achieved over unfertilized controls, while simultaneously improving postharvest shelf-life, vitamin C concentration, and lycopene synthesis (Mashamaite *et al.,* 2024; Zaato, 2025). Across multiple reviewed field trials, complete multi-nutrient formulations achieved absolute marketable yield increases ranging from 15% to 42% over unblended check treatments (Geremew *et al.,* 2026; Rahman *et al.,* 2021).

Nutrient-use efficiency and physiological interactions

A central goal of agronomic blending is maximizing the partial factor productivity of applied elements. Traditional fertilization practices suffer from low efficiency because high volumes of straight macronutrients saturate the soil solution, leading to fixation or environmental loss. The integration of advanced multi-nutrient blends and stabilized compound fertilizers effectively mitigates these pathways, significantly improving agronomic efficiency (AE) and apparent recovery efficiency (ARE) while limiting ammonia (NH_3) volatilization and greenhouse gas emissions like N_2O (Fixen *et al.,* 2015; Wu *et al.,* 2024).

Fertilizer regime	Average Agronomic Efficiency (AEN, kg fruit/kg N)	Apparent Recovery Efficiency (AREP, %)	Primary Loss Pathways Mitigated
Straight NPK (conventional)	12.4 - 15.8	15\% - 22\%	High leaching, rapid P-fixation in acidic soils
Multi-nutrient blends (+S, Zn, B)	22.1 - 28.5	31\% - 44\%	Antagonism reduction, rootnetworkexpansion, lower volatilization

This elevated efficiency is driven by improvements in root morphology and physiological processes within the plant root system. Balanced nutrition induces greater root length density and lateral root branching, expanding the volumetric zone of soil exploration (White and Broadley, 2009). At a biochemical level, elements like zinc act as key structural components of carbonic anhydrase and various dehydrogenases, which indirectly up-regulate the active transport proteins responsible for nitrate (NO_3) and phosphate (H_2PO_4) uptake across root cell membranes (Rahman *et al.,* 2021).

Furthermore, by integrating nitrification or urease inhibitors within stable compound multi-nutrient blends, studies demonstrate a simultaneous reduction in environmental footprint—such as a 38.5% drop in N2 emissions while maximizing the synchronization between crop demand and soil nutrient availability (Wu *et al.,* 2024). By managing the release and proximity of multi-elements, blended fertilizers successfully circumvent localized nutrient antagonism—such as the competitive inhibition of phosphorus over zinc uptake—promoting instead a balanced consumption profile that improves fertilizer recovery rates (Fixen *et al.,* 2015; Jing, 2025).

Future research

While the short-term agronomic benefits of multi-nutrient blended formulations are clear, several critical gaps must still be addressed to guide future agricultural development:

- **Long-term soil dynamics and residual chemistry:** Most existing research relies on short-term, single-season field or greenhouse trials. Long-term, multi-year field experiments across diverse soil classifications are urgently needed to assess the cumulative effects of multi-nutrient blending on soil organic matter, microbial ecology, baseline nutrient build-up, and the long-term risk of heavy metal or micro-element toxicities.
- **Smart nano-formulations and nano-coatings:** Future research should prioritize developing and testing advanced nano-enabled multi-nutrient delivery systems (e.g., chitosan or polymer-coated nano-fertilizers). Investigating how these responsive materials synchronize multi-element release with the specific developmental growth stages of the tomato plant can help maximize NUE and minimize environmental losses.
- **Synergistic organo-mineral and biochar composites:** There is a critical need to systematically map the interactions between synthetic multi-nutrient mineral blends and organic matrices, such as biochar, Black Soldier Fly compost, and custom bio-fertilizers. Research should focus on finding the optimal ratios that maximize nutrient retention, boost carbon sequestration, and stimulate soil enzymes.
- **Genotype by environment by management (G * E) interactions:** Future studies must explore how modern determinate and indeterminate tomato cultivars react to specific nutrient blends under variable environmental stressors, such as drought, salinity, or extreme heat. This will allow for the development of dynamic, region-specific blending formulas rather than relying on broad, regional generalizations.
- **Economic viability and smallholder adoption dynamics:** To move these technologies from the lab to the field, comprehensive life-cycle cost-benefit analyses are required. Researchers should evaluate the economic returns of custom blending for smallholder vegetable production systems, identifying the socioeconomic barriers to adoption and formulating policy strategies to improve market access to premium blended fertilizers.

CONCLUSION

This comprehensive review demonstrates that moving away from conventional, imbalanced blanket applications of straight macronutrients (NPK) toward tailored, multi-nutrient blended fertilizers is an essential paradigm shift for sustainable tomato (*Solanum lycopersicum* L.) production. Synthesized data across diverse agro-ecological zones confirms that the precise integration of primary macronutrients with essential secondary elements (Ca, Mg, S) and trace micronutrients (Zn, B, Fe) effectively resolves localized hidden hungers and physiological bottlenecks. This balanced nutritional approach significantly improves tomato vegetative growth parameters, such as plant height and leaf area index, and enhances key yield components, resulting in marketable fruit yield increases ranging from 15% to 42%.

Crucially, multi-nutrient blending technologies improve nutrient use efficiency (NUE) by expanding root network architecture and stimulating biochemical transport pathways. This minimizes environmental losses through ammonia volatilization, greenhouse gas emissions (N_2O), and nutrient leaching. Ultimately, multi-nutrient blended fertilization represents an ecologically sound and agronomically viable strategy to optimize tomato productivity, bolster human dietary health via micronutrient bio fortification, and safeguard soil resource longevity

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Current Horticulture 14(3): 25-33, July–September 2026

Research Review Article

DOI: 10.5958/2455-7560.2026.00034.8

Received: 9 April 2026; Revised: 04 May 2026: Accepted: 14 May 2026

Postharvest management and value-addition in ornamental crops: strategies for shelf-life extension and economic enhancement

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Abstract

Ornamental crops constitute a high-value component of horticulture but are highly perishable, resulting in substantial postharvest losses estimated at 30–40% under conventional supply chains. These losses arise from complex interactions among physiological, biochemical, and environmental factors, including respiration, ethylene sensitivity, water imbalance, and oxidative stress. This review critically synthesizes existing literature on postharvest physiology and management of ornamental crops, highlighting key determinants of senescence and evaluating current technologies for shelf-life extension. Comparative analysis of studies indicates that no single factor governs deterioration; rather, integrated effects of carbohydrate depletion, ethylene action, and xylem blockage collectively influence vase-life. Postharvest interventions such as pre-cooling, pulsing with preservative solutions, and maintenance of cold chain systems have demonstrated significant effectiveness, although their adoption remains limited by infrastructural constraints. Value-addition emerges as a complementary strategy to reduce losses and enhance profitability through conversion of flowers into dried products, essential oils, pigments, and nutraceuticals. However, lack of standardization, technical knowledge, and market linkages restricts large-scale implementation. Emerging approaches, including nanotechnology-based coatings, eco-friendly preservatives, and smart packaging systems, offer promising avenues but require further validation for commercial application. The review identifies critical research gaps in integrated postharvest management and sustainable value-addition, emphasizing the need for cost-effective, eco-friendly technologies and improved supply chain infrastructure to enhance the competitiveness of the floriculture sector.

Key words: Cold chain, Ethylene, Floriculture, Ornamental crops, Postharvest management, Reactive oxygen species, Senescence, Vase-life, Value-addition

Ornamental crops constitute a high-value segment of horticulture, with increasing global demand driven by urbanization, lifestyle changes, and expanding floriculture markets. The global cut flower market was valued at approximately USD 10.7 billion in 2024 and is projected to exceed USD 14 billion by 2030 (Faust and Dole, 2021), underscoring the economic significance of effective postharvest management. However, their commercial potential is severely constrained by high postharvest losses primarily due to physiological deterioration and inadequate supply chain management (Kader, 2002; Reid and Jiang, 2012). Earlier studies emphasized infrastructural limitations such as lack of cold chain and improper handling (Nowak and Rudnicki, 1991), more recent research highlights the dominant role of intrinsic physiological processes, particularly respiration, ethylene sensitivity, and water imbalance, in determining postharvest longevity.

Postharvest deterioration is now understood as a complex, multi-factorial process rather than a single-cause phenomenon. Classical work by Halevy and Mayak (1979) established the hormonal regulation of senescence, whereas subsequent studies by Reid and Jiang (2012) emphasized the interaction between ethylene and carbohydrate depletion. In contrast, van Doorn (1997) proposed that hydraulic failure due to xylem blockage is often the primary limiting factor in vase life. These differing perspectives indicate that postharvest longevity is governed by the interplay of metabolic, hormonal, and physical factors.

In parallel, value-addition has gained attention as a strategy to offset postharvest losses and improve profitability. While earlier approaches focused primarily on fresh flower marketing, recent studies demonstrate that processing into dried products, essential oils, and natural dyes can increase returns significantly and stabilize market fluctuations (Singh *et al.*, 2018; Shah *et al.*, 2022). However, despite its potential, adoption of value- addition technologies remained limited due to lack of standardization and infrastructure.

The review is based on a systematic survey of literature published between 1979 and 2026, drawn from peer-reviewed journals, book chapters, and conference proceedings. It differs from earlier reviews by integrating both the physiological basis of postharvest deterioration and practical value-addition strategies within a unified framework, with particular emphasis on emerging technologies and research gaps specific to the Indian floriculture sector. We have critically evaluated current knowledge on postharvest physiology, handling strategies, and value-addition in ornamental crops, with

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emphasis on identifying key determinants of senescence, comparing existing technologies, highlighting research gaps for sustainable floriculture development.

Postharvest Physiology and Constraints

Respiration and senescence

Respiration is widely recognized as a primary determinant of postharvest longevity due to its role in depleting carbohydrate reserves required for cellular maintenance (Halevy and Mayak, 1981; Reid and Jiang, 2012). Reid and Jiang (2012) suggested that the rapid carbohydrate depletion accelerates senescence and reduces vase life. However, this view has been challenged by van Doorn, who argued that carbohydrate status alone cannot explain wilting, emphasizing instead the role of hydraulic failure (van Doorn, 1997). This indicates that respiration interacts with other physiological processes rather than acting independently. Beyond substrate depletion, declining ATP availability compromises membrane ATPase activity, leading to electrolyte leakage and accelerated tissue senescence — a mechanism particularly relevant in petals with high metabolic rates (Ma *et al.,* 2018). Elevated midday temperatures increase respiratory activity; consuming carbohydrate reserves more rapidly and generating metabolic heat that exacerbates oxidative stress. Harvesting in cooler periods, such as early morning or late afternoon, reduces respiratory rates, conserves energy, and slows senescence (Ahmad *et al.*, 2014).

Role of ethylene

Ethylene is a key regulator of flower senescence, particularly in climacteric species such as carnation and rose (Halevy and Mayak, 1981; Reid, 1989). Early work by Halevy and Mayak demonstrated that ethylene accelerates petal wilting, abscission, and membrane degradation. Subsequent studies confirmed that even trace concentrations (as low as 0.1 $\mu L\ L^{-1}$) significantly reduce vase life (Pun *et al.,* 2003 and Baron *et al.,* 2021). However, species-specific variation in ethylene sensitivity suggests alternative regulatory pathways. Ethylene-insensitive flowers such as gladiolus and lily exhibit senescence more closely associated with carbohydrate depletion and oxidative stress (van Doorn, 2000). New regulators like salicylic acid, polyamines, and nitric oxide extend flower life by reducing ethylene production and enhancing cell functions (Tatte *et al.,* 2016). Use of ethylene scavengers, like 1-MCP, blocks ethylene binding sites, prolonging flower freshness (Hoppen 2020) while specifically, fumigation with EthylBloc improved rose display life, whereas Smart Fresh reduced ethylene production in cut carnations and roses (Nergi and Ahmadi, 2014).

Water relations and xylem blockage

Water balance is increasingly recognized as a critical determinant of postharvest longevity. Microbial proliferation at the cut stem ends leads to xylem blockage, restricting water uptake and causing wilting (van Doorn, 1997; van Doorn and Cruz, 2000). Experimental studies have shown that antimicrobial preservatives significantly improve solution uptake and extend vase life (Jain *et al.,* 2007; Jain *et al.,* 2014). Re-cutting stems at an angle under water removes air emboli and surface microbes, immediately restoring hydraulic conductance; this simple physical intervention, when combined with antimicrobial holding solutions, can increase water uptake by 40–60% compared to controls (van Doorn and Cruz, 2000). However, some researchers argue that vascular blockage alone cannot fully explain senescence, suggesting that it interacts with metabolic and hormonal processes (Jones and Hill, 1993). Thus, water relations represent a central but interdependent factor in postharvest deterioration.

Oxidative stress and biochemical changes

Oxidative stress has emerged as a key mechanism underlying senescence. Accumulation of reactive oxygen species (ROS) and decline in antioxidant enzymes such as SOD, CAT, and peroxidases lead to membrane lipid peroxidation and cellular damage (Tripathi and Dubey, 2004; Ma *et al.,* 2018). Importantly, ROS also upregulate ACC synthase activity, creating a positive feedback loop between oxidative stress and ethylene biosynthesis that further accelerates the rate of senescence (Ma *et al.,* 2018). Application of antioxidant compounds such as ascorbic acid has been shown to maintain enzyme activity and delay senescence in chrysanthemum (Jain and Janakiram 2016; Varun *et al.,* 2018a and 2018 b). However, the effectiveness of such treatments varies across species, indicating the need for crop-specific optimization. Varun *et al.,* (2019) reported that spraying of 100 ppm ascorbic acid on cut chrysanthemum cv. Pusa Centenary significantly improved vase-life by maintaining chlorophyll content, enhancing membrane stability, and regulating antioxidant enzymes (SOD, CAT, POX).

It reduced oxidative stress (H_2O_2 accumulation) and effectively delayed leaf yellowing and p*etal* senescence compared to untreated flowers. Application of boric acid (4%) and salicylic acid (50 ppm) in tuberose, particularly when combined with muslin cloth packaging, enhanced antioxidant enzyme activities (CAT, SOD, and guaiacol peroxidase) under both ambient and cold storage. Enzyme activity generally increased during storage and declined at the end of vase-life, indicating their role in delaying senescence and maintaining flower quality

(Singh *et al.,* 2023). Enzyme-mediated degradation of proteins and cell wall components further contributes to tissue softening and petal abscission (Kenichi *et al.,* 2016).

Synthesis and research gaps

The postharvest deterioration is governed by the interaction of respiration, ethylene signaling, water imbalance, and oxidative stress (van Doorn and Curz, 2000; Reid and Jiang, 2012). However, most research has focused on individual factors rather than integrated mechanisms. There is a need for systems-level approaches and greater emphasis on eco-friendly preservative technologies.

Harvesting and handling

Harvest maturity significantly influences postharvest performance, with optimal stage varying across species and market requirements (Nowak and Rudnicki, 1991; Kader, 2002). Long-distance transport necessitates earlier harvesting at the tight bud stage (Faust and Dole 2021). Early harvesting improves transportability but may limit flower opening, whereas late harvesting enhances aesthetics but reduces vase-life. Loose flowers like jasmine, crossandra and tuberose are harvested at bud stage which have several advantages like ease of treatment with preservatives, packaging, transport, withstanding rough handling, moreover, the flower buds are insensitive to ethylene. Flowers harvested at more advanced stage of development have shorter vase life than younger flowers. Coordinated harvesting aligned with diurnal physiology—especially during cooler periods such as early morning—optimizes water status, conserves carbohydrate reserves, reduces field heat and evaporative water loss, lowers respiration stress, and slows senescence, thereby sustaining cut flower quality and extending vase life, whereas midday or afternoon harvesting increases water stress and accelerates senescence (Varu and Barad, 2007; Taylor *et al.,* 2008).

Pre-cooling is widely recognized as an effective method for reducing respiration and ethylene production (Kader, 2002, Jain *et al*, 2018). For instance, vacuum cooling of cut roses to 1–2°C within 30 minutes of harvest has been shown to reduce respiration rate by 50–60% and extend vase life by 3–4 days compared to ambient-cooled controls (Cevallos and Reid, 2001). However, its adoption is constrained by infrastructural limitations in many regions. Floral preservatives are essential for improving colour, flower size, and shelf life in loose flowers (Rudnicki *et al.* 1991). These preservatives typically contain sugars like sucrose, which acts as a food source, slows protein degradation and maintains turgidity (Rani and Singh 2014). Pulsing treatments with sucrose and antimicrobial agents such as 8-HQC, citric acid, and aluminium sulphate have consistently been shown to improve water uptake and vase life (Jain *et al.,* 2007; Jain *et al.,* 2017). Recent studies have explored eco-friendly alternatives such as salicylic acid and sulpho-salicylic acid, although their commercial applicability remains limited (Jain *et al.,* 2021).

Postharvest life of flowers can be controlled by growth regulators. Growth regulators modulate postharvest longevity through distinct hormonal pathways. Cytokinins (*e.g.,* thidiazuron) delay leaf and petal senescence by maintaining chlorophyll content and protein synthesis. Gibberellins (GA_3) at optimized concentrations promote floret opening and extend longevity, whereas abscisic acid (ABA) generally accelerates senescence; however, at very low concentrations (~1 ppm) in continuous holding solution, it delays wilting and extends the longevity of cut roses by inducing stomatal closure. Depending upon the concentrations, GA_3 in some cases promotes longevity of flowers, while it is also used in bud opening solution. The senescence and abscission of poinsettia flowers is delayed by auxin (Siddiqui, 2015). Nitric oxide donors such as sodium nitroprusside suppress ethylene biosynthesis across multiple species, further extending postharvest life (Mortazavi *et al.,* 2011). There are some new generation growth regulators which improve the postharvest life and attributes of flowers (Table 1).

Storage, packaging and transportation

Temperature is the most critical factor in maintaining flower quality during storage (Jain *et al.* 2011). Lower storage temperatures decrease respiration, reduced water loss metabolic activity, ethylene synthesis, and disease development, increasing post-harvest durability (Cevallos and Reid, 2001). Cold storage of cut flowers can be done by wet or dry methods. Wet storage, where stems are kept in water, is suitable for short durations, while dry storage allows longer storage and space efficiency but is more labour-intensive and not suitable for all flowers. Key factors such as temperature, relative humidity, air composition, and circulation significantly influence postharvest quality (Cevallos and Reid, 2001). Controlled atmosphere storage, involving low O_2, elevated CO_2, and reduced ethylene, helps delay senescence by slowing respiration.

Verma *et al.,* (2006) reported that, dry storage of chrysanthemum cv. Snow Ball showed that wrapping flowers in wax paper and storing them under cold conditions for 24 hours resulted in maximum vase life, better flower size, higher sugar content, and minimal

Table 1: New generation plant growth regulators and their mode of action

Growth regulator	Mode of action	Examples	Reference
Salicylic acid	1. It has a pH of 2.4 and acidic solution inhibits bacteria growth and proliferation. 2. Modulate plant responses to a wide range of oxidative stresses and prevents cell wall degradation. 3. SA suppresses ACC synthase and ACC oxidase activities, biosynthesis of ethylene, and improves the postharvest life.	Alstroemeria, *Lilium, Rose, Gerbera* and *Tuberose*	Bayat and Aminifard, 2017
Polyamines (Putrascine, Spermine and Spermidine)	Role in sugar biosynthesis, Stimulation of cell division, maintains integrity of cell membrane and delays senescence. Free radical scavenger, increases water uptake, high retention of fresh weight and p*etal* sugar status, low electrolyte leakage.	Rose, gerbera, carnation, lilium etc	Sumathi *et al.,* 2015
Nitric oxide (sodium nitroprusside) as Nitric oxide) donor	Endogenous plant signal molecule, decreased 1-aminocyclopro-pane-1- carboxylate oxidase (ACO) activity and ethylene production. Hormone modulation, programmed cell death and wounding and defense responses	Rose, carnation	Mortazavi *et al.,* 2011
Thiodiazuron (N-phenyl-N-l, 2, 3-thiadiazol-5-Urea)	Non-metabolized Cytokinin, promote the conversion of cytokinin ribonucleotides to more biologically active Ribonucleosides, strong cytokinin-like activity, prevent leaf senescence	Alstroemeria, stock, lilies, tulips and potted plants, including geranium, freesia, Ornithogalum, and *Euphorbia fulgens*	Macnish *et al.,* 2010

weight loss. Controlled atmosphere storage further delays senescence by modifying gas composition, although its adoption is limited due to cost constraints (Nowak and Rudnicki, 1990). Modified atmosphere packaging (MAP), which uses semi-permeable plastic films, has limited application in cut flowers due to its requirement for consistently low temperatures, though it can extend the life of crops like carnations. In contrast, Modified Interactive Packaging (MIP) is more adaptable, as gas composition inside the package adjusts dynamically based on temperature and flower maturity. MIP offers greater temperature tolerance and reduces transpiration by maintaining high relative humidity. It slows flower metabolism through slight increases in CO_2 and reduced O_2 levels, thereby extending postharvest life. This makes MIP particularly useful for long-distance transport, including sea shipment, or for storage before peak demand periods such as Valentine's Day (Bishop, 2007).

Packaging materials play a protective role against mechanical damage and moisture loss, though environmental concerns regarding synthetic materials are increasing (Ahvenainen, 2003). Cellophane wrapping was most effective in maintaining postharvest quality of rose cv. First Red. Flowers wrapped in cellophane and stored at 2°C for 3 days showed improved vase life, higher water uptake, better flower size, greater retention of proteins and sugars, and minimum weight loss compared to other treatments. (Jain *et al.,* 2006). Packaging significantly affects the postharvest quality of loose tuberose cv. Arka Prajwal. Among the treatments, HDPE (51 µm) packaging performed best, especially under cold storage and also improved quality under ambient conditions compared to control.

Overall, HDPE bags were most effective in extending shelf life and maintaining flower quality (Singh *et al.,* 2024). Shrink-wrap (Cryovac®) and HDPE packaging were most effective, extending shelf life of African marigold cv. Pusa Bahar up to ~19 days under cold storage and 4.5 days under ambient conditions. Shrink-wrap also maintained key quality attributes (moisture, color, membrane stability, and antioxidants) while reducing weight loss and respiration. Improved antioxidant enzyme activity (SOD, CAT, POD) contributed to delayed senescence, making shrink-wrap the most effective packaging method (Viresh *et al.,* 2024). Similarly, shrink-wrap proved most effective, for extending its post-harvest life and quality attributes in both African and French marigold cultivars, suggesting its strong potential for commercial adoption to enhance marigold storability and reduce post-harvest losses (Kumar *et al.,* 2025).

Transportation remains a critical limitation, as lack of refrigerated systems leads to rapid quality deterioration (Wills, 1998). Road and air transport are the primary modes for moving cut flowers (Nowak and Rudnicki, 1990). Refrigerated trucks are used for regional transport, while air transport is preferred for long-distance shipping, sometimes supplemented with ice or dry ice to manage heat load (Wills, 1998). In the absence of cooling, proper ventilation helps reduce respiration heat and ethylene buildup. Rail and refrigerated sea containers also offer viable options, particularly for durable flowers like bud-stage carnations under controlled atmosphere (CA) conditions (Macnish *et al.,* 2009). Maintaining the cold chain is critical; re-cooling and rehydration—by re-cutting stems and placing them in treated water—help preserve postharvest quality during handling and distribution.

Cold chain management (CCM)

Effective CCM begins at the farm and continues until the product reaches the final consumer, making it a key strategic advantage in the floriculture industry. It requires strict temperature regulation and prompt corrective actions in case of delays or temperature fluctuations. Maintaining optimal temperature at every stage of the supply chain is essential to preserve product quality (van der Hulst, 2004). Research indicates that even a single temperature excursion above 10°C during transit can reduce vase life by 2–3 days for sensitive crops like roses and gerberas, highlighting the importance of uninterrupted cold chain maintenance (Staby and Reid, 2005). However, temperature variations during handling and transportation can still reduce its efficiency (Staby and Reid, 2005). Studies have shown that storing loose marigold flowers at low temperatures can extend shelf life up to twofold (Viresh *et al.,* 2024; Kumar *et al.,* 2024). Similarly, cold storage of loose tuberose cv. Arka Prajwal significantly improves postharvest attributes such as flower diameter, opening, color retention, and extends shelf life up to six days (Singh *et al.,* 2024).

Value- addition

Value-addition in floriculture significantly enhances economic returns by transforming highly perishable raw flowers into diversified, high-value products with improved marketability (Vijay and Baweja, 2025). Such interventions, including drying, extraction, and processing, convert low-value produce into premium commodities, thereby increasing overall profitability of the floriculture enterprise (Shah *et al.,* 2022). Farmers and entrepreneurs can achieve substantial profit enhancement—often ranging from 50% to 100%—as value-added products such as essential oils, dried flowers, floral crafts, and edible derivatives fetch higher prices than fresh flowers in conventional markets (Koushal *et al.,* 2024). For example, essential oil extraction from rose petals in Kannauj, India, yields return 3–5 times higher than fresh flower sales at wholesale markets, while dried statice and gomphrena products fetch 2–3× the fresh flower price in export markets (Shah *et al.,* 2022). Furthermore, value- addition reduces dependence on volatile fresh flower markets and helps stabilize income during periods of oversupply and price crashes (Vijay and Baweja, 2025).

Another important economic advantage is the development of off-season and shelf-stable products through value-addition (Koushal *et al.,* 2024). Since fresh flowers have a limited vase-life and high perishability, processing techniques such as dehydration, freeze-drying, and extraction extend their usability and market availability (Sindhu and Gupta, 2024). Shelf-stable products like potpourri, essential oils, natural dyes, and nutraceuticals enable year-round marketing and facilitate access to export markets, thereby increasing overall value chain efficiency (Koushal *et al.,* 2024). In addition, improved postharvest technologies contribute to quality retention and extended storage life, further enhancing economic returns from floricultural produce (Harish *et al.,* 2026).

Value-addition also contributes significantly to waste minimization and supports the concept of a circular economy in floriculture systems (Tiwari and Bisen, 2024). A considerable proportion of flowers estimated at around 30–40% is lost due to perishability and inadequate postharvest handling practices (Tiwari and Bisen, 2024). These floral wastes can be effectively utilized for producing value-added products such as biofertilizers, essential oils, natural pigments, incense sticks, and bioenergy, thereby converting waste into economic resources (Dutta *et al.,* 2021). This approach aligns with circular bioeconomy principles, where biological waste streams are recycled into productive uses, reducing environmental burden and generating additional income opportunities (Kumar *et al.,* 2025). Moreover, such sustainable utilization of floral biomass promotes rural entrepreneurship, employment generation and efficient resource utilization in the floriculture sector (Koushal *et al.,* 2024).

Natural essential oils are volatile aromatic compounds extracted from floral, foliar, stem, and woody plant tissues through steam distillation, cold pressing, or solvent extraction. Their applications span aromatherapy, cosmetics, perfumery, and pharmacological uses owing to their antioxidant, antimicrobial, and anxiolytic properties (Lobo *et al.,* 2022). India's fragrance market is rapidly growing, projected to rise from $1.25 billion in 2025 to nearly $2 billion by 2034, with the attar segment expanding even faster due to its natural and cultural appeal. Attars, being alcohol-free and made from natural flowers like rose and jasmine, are valued for their long-lasting fragrance, skin-friendliness, and are increasingly positioned as premium wellness and luxury products (Aroma Craft Blog March 29, 2026).

Tinted flowers often fetch higher prices in the market as they enhance visual appeal and allow the addition of one or more attractive colours to cut flowers, thereby increasing their aesthetic value. In crops like tuberose, tinting serves as an effective value-addition technique alongside its natural fragrance. Studies have shown that use of edible dyes, particularly raspberry red, can improve vase life, reduce floret drying, and enhance overall consumer acceptance (Jain *et al.,* 2015). Similarly, research on chrysanthemum, tuberose, and lilium indicates that dye type and immersion duration significantly affect vase life, moisture content, and colour quality, with blue, green, and orange dyes providing better colour intensity and consumer preference, while optimal immersion time helps maintain freshness and longevity (Pavan *et al.,* 2022). It is important to note that dyes intended for fresh flower tinting must comply with food safety regulations (FSSAI in India; FDA in the US) when flowers are destined for culinary or medicinal use, necessitating careful selection of approved colorants.

Eco-friendly dry flower products have great potential, especially in cold regions where fresh flowers are scarce. Proper drying of long-lasting flowers helps retain their color and quality, increasing their value in markets. These products are often profitable, depending on costs, finishing, packaging, and shelf life. Flowers like statice, gomphrena, rose, sunflower, and zinnia are ideal as they remain attractive after drying. Using protective methods such as lamination or plastic coverings helps prevent insect and fungal damage while preserving their natural appearance, making them more appealing to buyers (Singh and Kumari, 2023.) Embedded drying of roses using silica gel combined with a hot air oven is widely reported as an effective preservation method. Bhutani (1990) and Datta (2004) have shown that embedding flowers in desiccants like silica gel helps maintain shape and absorb moisture, while controlled oven drying improves color retention and overall quality.

This technique is therefore commonly recommended for producing high-quality dried rose products. Vacuum drying is the most effective method for preserving color, texture, and overall quality of *Gerbera hybrida* 'Ruby Red' dried flowers. However, microwave drying helps retain flower size, vacuum drying gives the best overall results for long-term preservation (Namita *et al.,* 2018). Techniques such as glycerin drying have proven effective in preserving foliage quality and enhancing product appeal. A ratio of 1:3 (glycerin-to-water) was found to be most suitable for preserving foliage like silver oak, asparagus, cordyline, and fern, as it ensured better moisture retention, quicker drying, and improved overall quality (Singh *et al.,* 2018). Natural dye extraction from flowers offers eco-friendly alternatives for textile and food industries, but challenges remain in improving stability and scalability.

There is a growing shift from synthetic dyes to natural pigments due to health concerns like toxicity and carcinogenic effects, along with increasing consumer demand for safe and eco-friendly products. Natural dyes offer added benefits such as antioxidant, antimicrobial, and nutritional properties, though they can be more expensive and may affect flavour or aroma (Mohammad *et al*, 2022). Keerthana *et al.,* (2026) optimized anthocyanin extraction from rose petals using Response Surface Methodology, finding maximum yield under mild acidic conditions (0.014–0.015% HCl), low temperature (25°C), and a 1:5 ratio. It also showed that the pigment is most stable at low temperatures, acidic pH (1–3), and dark storage, while heat, light, and alkaline conditions accelerate degradation.

Emerging Trends

Nanotechnology and bio-based coatings

Nanotechnology-based coatings have shown potential in reducing transpiration and microbial growth, thereby improving postharvest quality (Sharma *et al.,* 2025). Silver nanoparticles (AgNPs, 10–50 nm) inhibit microbial growth at cut stem surfaces and reduce xylem blockage, while titanium dioxide (TiO_2) coatings lower ethylene-mediated senescence through photocatalytic degradation of ethylene under light exposure. Zinc oxide (ZnO) nanoparticles have additionally shown ROS-scavenging activity, synergizing with antioxidant-based postharvest treatments (Sharma *et al.,* 2025). Eco-friendly preservatives derived from plant extracts are gaining attention as sustainable alternatives (Bhandari *et al.,* 2026).

Smart packaging digital supply chain and genetic engineering

Smart packaging and IoT-based monitoring systems enable real-time tracking of storage conditions, improving supply chain efficiency (Rashed *et al.,* 2024). Several advanced methods, including physical, chemical, and emerging treatments like nanoparticles, melatonin, and essential oils, have been developed to enhance flower freshness. Recent advances in physical treatments (e.g. LED light, ozone, gamma radiation) and the application of bioactive compounds like melatonin, polyamines, and essential oils offer promising results in improving flower longevity (Jain *et al.,* 2025). Genetic engineering offers a promising avenue for developing senescence-tolerant varieties through targeted suppression of ethylene biosynthesis genes (ACS/ACO) or overexpression of antioxidant genes, thereby inherently extending postharvest longevity.

Environment-friendly practices

In flower processing, environmentally friendly practices are becoming increasingly important.

Eco-friendly extraction methods, such as the use of natural solvents or organic techniques, help minimize environmental impact, while zero-waste approaches ensure that all parts of the flower—petals, stems, and leaves—are utilized efficiently, reducing waste. Additionally, the use of biodegradable or recyclable packaging supports sustainability and meets the growing consumer demand for eco-conscious floral products [Shobna *et al* 2023]. Cold-pressed essential oils are widely used in high-end perfumes, luxury cosmetics, and aromatherapy because they retain the natural aroma and purity of the flowers. This method preserves volatile compounds, resulting in a richer and more complex fragrance profile, making the oils highly suitable for wellness and therapeutic applications. (Lobo *et al*, 2022).

CONCLUSION

Postharvest management of ornamental crops involves a complex interaction of physiological, biochemical, and environmental factors that determine flower quality and longevity. Although advancements have been made in understanding respiration, ethylene action, water relations, and oxidative stress, their integrated management remains challenging. Improved harvesting, handling, cold chain systems, and advanced storage and packaging can significantly reduce losses, but limitations in infrastructure and standardization persist. Value-addition further enhances profitability by converting perishable flowers into high-value products such as essential oils, dried flowers, natural dyes, and tinted blooms. This not only increases market value but also ensures income stability and year-round utilization.

The integration of sustainable practices, eco-friendly technologies, and innovations like smart packaging and bio-based treatments highlights the strong potential of floriculture for economic growth, environmental sustainability, and rural entrepreneurship. Future research priorities should include: (i) development of integrated postharvest management protocols combining physiological, chemical, and physical interventions specific to major ornamental crops; (ii) techno-economic analysis of value-addition supply chains to identify cost-effective entry points for smallholder farmers; (iii) field validation of nanotechnology-based and bio-based preservatives under Indian agroclimatic conditions; and (iv) use of omics approaches (transcriptomics, metabolomics) to identify novel senescence-related molecular targets for genetic improvement of vase-life.

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Current Horticulture 14(3): 34-41, July–September 2026
DOI: 10.5958/2455-7560.2026.00035.X
Received: 9 April 2026; Revised: 3 September 2026 Accepted: 4 September 2026

Research Review Article

Bougainvillea as a shield against urban air pollution: mechanism, tolerance assessment and phytoremediation

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Abstract

Metropolitan cities across the globe are grappling with deteriorating outdoor air quality driven by rapid urbanization, industrial expansion, and intensifying vehicular traffic. Nature-based solutions, particularly phytoremediation through strategically deployed ornamental plants, offer a sustainable, economically-viable, and visually enriching pathway to counteract this challenge. The present review systematically examines the physiological and morphological mechanisms that enable ornamental plants to intercept particulate matter and metabolize gaseous pollutants such as nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ground-level ozone (O_3). The Air Pollution Tolerance Index (APTI) is critically evaluated as a screening tool for selecting robust species suitable for urban green belts. Special focus is placed on Bougainvillea, a widely cultivated tropical ornamental plant, whose distinctive leaf surface morphology, high tolerance to drought, and documented capacity for lead (Pb), cadmium (Cd), NO_2, and particulate matter accumulation render it an exceptional candidate for urban phytoremediation. Evidence from metropolitan case studies spanning Delhi, Mumbai, Metro Manila, and Beijing is synthesized to highlight practical successes and context-specific constraints. Considerations regarding green infrastructure design, species selection, and future research priorities are also discussed. Collectively, this review reinforces the case for embedding ornamental phytoremediation into mainstream urban planning policies.

Key words: Air Pollution Tolerance Index, Bougainvillea, Particulate matter, Phytoremediation, Ornamental Plants, Urban greening

Unprecedented pace of urban expansion witnessed during the past five decades has fundamentally altered the atmospheric chemistry of cities across the world. Emissions from millions of motor vehicles, energy-intensive industries, construction sites, and domestic combustion collectively generate a complex burden of primary and secondary pollutants that now exceed safe threshold limits in most megacities (WHO, 2022). Among these, fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ground-level ozone (O_3) stand out for their documented toxicity to human respiratory and cardiovascular systems (Manisalidis *et al.,* 2020). Engineering-based interventions such as catalytic converters, industrial scrubbers, and electrostatic precipitators have contributed meaningfully to reducing point-source emissions; however, they remain prohibitively expensive, energy-intensive, and largely ineffective against diffuse, traffic-related pollution at the street level. This has prompted a global scientific interest in nature-based solutions, of which phytoremediation — the deliberate deployment of living plants to intercept, accumulate, or biochemically transform environmental contaminants — has emerged as a particularly promising and multi-functional strategy (Rocha *et al.,* 2022; Piacentini and Di Baccio, 2024).

Ornamental plants occupy a special niche in this discourse because they simultaneously deliver ecosystem services and aesthetic enrichment without entering the agricultural food chain, thereby eliminating the risk of toxin transfer to human or animal consumers (Francini *et al.,* 2022). Decades of applied research at ICAR-Indian Agricultural Research Institute (IARI), New Delhi, have highlighted the multifunctional potential of ornamental species not only for beautification but also for ecological services in urban and peri-urban settings (Singh *et al.,* 2019; Jain *et al.,* 2020). Studies on indoor air purification through potted plants have further demonstrated the relevance of ornamental flora in managing sick-building syndrome and confined-space pollution (Tiwari *et al.,* 2019a). Earlier work on floriculture development in India has comprehensively documented the diversity of available ornamental species and their adaptability to varied agro-climatic conditions, providing a valuable foundation for urban greening programmes (Jain *et al.,* 2022a).

Among ornamental taxa evaluated for pollution tolerance, Bougainvillea has consistently attracted attention owing to its vigorous growth, xeric adaptability, striking bract display, and documented tolerance to atmospheric contaminants. A practical guide to quality seedling production of Bougainvillea published by scientists of this laboratory (Jain *et al.,* 2019) further

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underscores its horticultural and environmental relevance for urban programmes. The present review synthesizes contemporary evidence on ornamental plant-based air pollution mitigation, with concentrated emphasis on Bougainvillea, and offers a critical appraisal of mechanisms, metrics, case studies, and pathways for mainstreaming this approach in metropolitan planning.

Urban Air Pollution: Sources and Health Implications

Urban air is a dynamic mixture of gases and aerosols generated by both anthropogenic and natural processes. The principal pollutants of concern in metropolitan contexts are particulate matter (PM), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs) (Seinfeld and Pandis, 2016). Vehicular traffic constitutes the dominant anthropogenic source of NO_x and PM in most cities, with power generation, industrial combustion, construction activities, and resuspended road dust contributing additional loads (EEA, 2023).Particulate matter is conventionally partitioned by aerodynamic diameter into coarse particles (PM_{10}, ≤10 μm) and fine particles ($PM_{2.5}$, ≤2.5 μm). Fine particles are of greater toxicological concern because they penetrate deep into the alveolar region of the lungs and may translocate to the bloodstream, inducing systemic inflammation (Pope and Dockery, 2006). Long-term exposure to $PM_{2.5}$ is strongly associated with chronic obstructive pulmonary disease (COPD), ischaemic heart disease, stroke, and lung cancer (Schraufnagel *et al.,* 2019). Children, pregnant women, the elderly, and individuals with pre-existing cardiorespiratory conditions bear a disproportionate burden of these health outcomes (Manisalidis *et al.,* 2020).

Heavy metals constituting a trace fraction of urban PM represent an additional hazard. Lead (Pb), cadmium (Cd), arsenic (As), and zinc (Zn) originate largely from vehicular exhaust, tyre and brake abrasion, and smelting operations. Research conducted on warm-season turf grasses irrigated with wastewater in an urban Indian setting revealed significant accumulation of heavy metals in plant tissues, reaffirming the pathway through which plants intercept and bio-concentrate atmospheric and soil-borne metal pollutants (Balaji *et al.,* 2025). Complementary investigations on marigold and calendula subjected to heavy-metal-spiked wastewater irrigation documented species-specific translocation factors and tolerance thresholds, providing a quantitative basis for ornamental plant use in contaminated urban soils (Verma *et al.,* 2023; Vignesh *et al.,* 2023).

Phytoremediation: concept and mechanisms

Phytoremediation is a solar-energy-driven remediation technology that exploits the inherent biological and biochemical capabilities of plants to remove, immobilize, or transform environmental contaminants present in soil, water, or air. When applied to the atmospheric compartment, it capitalises on two broad categories of processes: physical deposition of particles onto foliar surfaces, and biochemical assimilation of gaseous pollutants through the stomatal pathway (Nowak *et al.,* 2014; Piacentini and Di Baccio, 2024).

Particulate matter interception

The interception and retention of airborne particles by plant canopies is governed by an interplay of aerodynamic, gravitational, and surface-adhesion forces. Turbulent deposition, impaction, and sedimentation collectively deliver particles from the ambient air stream onto leaf surfaces (Beckett *et al.,* 2000). The efficiency of this process is profoundly influenced by leaf micromorphology. Leaves bearing dense trichomes (leaf hairs), pronounced epidermal ridges, and waxy cuticular layers exhibit markedly superior particle retention relative to smooth, glabrous surfaces (Weerakkody *et al.,* 2018; Sgrigna *et al.,* 2015). Rainfall events periodically wash deposited particles from leaves to the soil surface, effectively transferring the pollutant load from the atmospheric compartment to the pedosphere where further microbial and chemical transformations can occur (Chen *et al.,* 2017).

Stomatal uptake and metabolism of gaseous pollutants

Gaseous air pollutants enter leaf mesophyll tissue principally through stomatal apertures during daylight hours when gas exchange is most active. Once inside the sub-stomatal cavity, NO_2 is dissolved into the apoplastic water film and enzymatically reduced to nitrite, then further assimilated into amino acids via the glutamine synthetase/glutamate synthase (GS/GOGAT) pathway (Takahashi and Morikawa, 2014). Sulphur dioxide is oxidised to sulphate, which is subsequently incorporated into cysteine and other sulphur-containing organic compounds. Ozone, a potent oxidant, reacts with mesophyll cell membranes, generating reactive oxygen species (ROS); tolerant species counteract this through up-regulation of ascorbate peroxidase, superoxide dismutase, and catalase activities. The leaf phyllosphere microbiome also contributes to the degradation of certain organic gaseous pollutants, adding a microbial dimension to plant-mediated air purification (Papen and Gessler, 2019). Studies on ornamental chrysanthemum at IARI have shown that leaf biochemistry — particularly chlorophyll stability and osmolyte accumulation under stress — directly reflects the capacity of plants to withstand oxidative insults analogous to those imposed by air pollution (Vanlalruati *et al.,* 2023; Vanlalruati *et al.,* 2021).

Air Pollution Tolerance Index (APTI): Principle and Application

A scientifically grounded approach to urban species selection requires quantitative tools that rank plants by their resilience to pollution stress. The Air Pollution Tolerance Index (APTI), originally conceived by Singh and Rao (1983), integrates four key leaf biochemical parameters into a composite score that reliably distinguishes sensitive from tolerant species. The index is calculated as:

$$APTI = [A (T + P) + R] / 10$$

where A = ascorbic acid content (mg g^{-1} fresh weight); T = total chlorophyll content (mg g^{-1} fresh weight); P = pH of leaf extract; and R = relative water content (%). Each parameter captures a distinct dimension of pollution resilience. Ascorbic acid serves as a front-line antioxidant quenching ROS generated by oxidising pollutants (Agbaire and Esiefarienrhe, 2009). Chlorophyll integrity reflects the photosynthetic machinery's capacity to continue functioning under pollutant load — a relationship well documented in ornamental crops including chrysanthemum (Joshi and Swami, 2009; Vanlalruati *et al.,* 2021). Leaf pH modulates enzyme activity in detoxification pathways, while relative water content indicates stomatal regulation competence (Rai and Panda, 2014).

Based on their APTI scores, plant species are categorised as: sensitive (APTI < 10), intermediate (APTI 10–16), or tolerant (APTI > 16). Species occupying the tolerant category are recommended for planting in high-exposure sites such as highway medians, industrial buffer zones, and roadside green belts. Sensitive species, conversely, serve as early-warning bioindicators, with visible foliar injury providing a non-instrumental signal of elevated pollution episodes. Tolerant ornamental species identified through APTI screening thus form the backbone of effective urban phytoremediation programmes (Singh and Rao, 1983; Rai and Panda, 2014).

Ornamental Plants in Urban Phytoremediation: An Overview

Ornamental horticulture has traditionally been evaluated through the prism of aesthetics, productivity, and postharvest quality; however, an expanding body of literature now recognises its ecological service dimension. The fact that ornamental species are not harvested for human or animal consumption eliminates the toxin-transfer risk that constrains the use of food or forage crops in contaminated urban environments (Asgari Lajayer *et al.,* 2019). This inherent biosafety advantage, combined with the psychological and societal benefits of living greenery, positions ornamental phytoremediation as an eminently practical urban health intervention (Francini *et al.,* 2022).

India's floriculture sector, characterised by remarkable species diversity and expanding urban demand, offers a substantial reservoir of candidate phytoremediators. A comprehensive status and prospects report on Indian floriculture (Jain *et al.,* 2022a) catalogued the wide spectrum of ornamental crops commercially cultivated in the country, many of which demonstrate morphological and physiological attributes favourable for pollution interception. Assessments of foliage potted plants for urban and peri-urban environments conducted at ICAR-IARI confirmed that several commonly available indoor and outdoor species perform well under the abiotic stress conditions typical of Indian cities (Jain *et al.,* 2020). Urban landscaping strategies, when designed with species selection underpinned by pollution tolerance data, can meaningfully contribute to ambient air quality improvements while simultaneously fulfilling civic beautification objectives (Singh *et al.,* 2019).

Table 1: Air Pollution Tolerance Index (APTI) of selected ornamental plant species

Plant species	Family	APTI value	Tolerance category	Recommended use
Bougainvillea spectabilis	Nyctaginaceae	14.2	Intermediate	Roadside hedges, green belts
Hibiscus rosa-sinensis	Malvaceae	16.8	Tolerant	Urban parks, buffer zones
Ixora coccinea	Rubiaceae	12.5	Intermediate	Ornamental gardens
Nerium oleander	Apocynaceae	15.3	Intermediate	Highway medians, industrial areas
Rosa sp.	Rosaceae	11.8	Intermediate	Residential gardens
Chrysanthemum sp.	Asteraceae	13.6	Intermediate	Indoor/outdoor landscaping
Mixed Ferns	Various	10.2	Intermediate	Shaded areas, ground cover

Plants with high leaf area index (LAI), dense branching architecture, and persistent foliage extend the duration and spatial extent of particle deposition. Rapid growth and high biomass turnover further amplify the quantity of pollutants sequestered per unit time, while regular pruning facilitates the physical removal of accumulated toxin-laden biomass from the urban system. The integration of ornamental planting with engineered green infrastructure — road green belts, vegetated walls, and green roofs — multiplies these benefits by creating continuous phytoremediation corridors within the urban matrix (Abhijith *et al.,* 2017).

Bougainvillea: an outstanding ornamental phytoremediator

Bougainvillea (Bougainvillea Comm. ex Juss.) family Nyctaginaceae, native to the coastal and tropical forests of South America, has been naturalized across tropical and subtropical urban landscapes worldwide. Its prolific growth, tolerance to periodic drought, and minimal maintenance requirements made it a mainstay of Indian urban horticulture decades before its phytoremediation potential was systematically investigated. Research emanating from ICAR-IARI, New Delhi has addressed the horticultural management of this species, including the standardization of quality seedling production protocols that ensure uniform, vigorous planting stock for urban programmes (Jain *et al.,* 2019), providing a crucial practical link between laboratory science and field deployment.

Foliar morphology and particulate matter retention

The leaf surface of Bougainvillea spectabilis is characterised by a moderately rough adaxial epidermis, the presence of uni- and multicellular trichomes, and a wax-coated cuticle — features collectively identified as determinants of superior particle adhesion (Weerakkody *et al.,* 2018). Seasonal measurements of foliar dustfall on Bougainvillea leaves in polluted urban settings have confirmed significant accumulation of total suspended particles and PM_{10} fractions, validating its status as an effective phytomonitor and passive phytoremediator for particulate pollution (Prajapati and Tripathi, 2008). Annual $PM_{2.5}$ removal efficiency of approximately 8.5 g m^{-2} leaf area and PM_{10} removal of 15.2 g m^{-2} have been reported, placing Bougainvillea among the better-performing ornamental species in this regard (Das and Prasad, 2012; Table 2).

Nitrogen Dioxide tolerance and assimilation

Traffic-generated NO_2 represents one of the most pervasive gaseous pollutants in Indian metropolitan corridors. Experimental fumigation studies have shown that Bougainvillea can absorb and metabolise significantly elevated ambient NO_2 concentrations (45–120 µg m^{-3}) over continuous exposure periods without exhibiting severe visible phytotoxicity symptoms (Singh and Agrawal, 2007; Das and Prasad, 2012). The absorbed NO_2 is enzymatically processed through nitrate reductase pathways and assimilated into organic nitrogen compounds, effectively removing the pollutant from the atmospheric pool. This biochemical flexibility, combined with high leaf area per plant, translates into substantial NO_2 removal rates per unit of planted area in road green belts.

Heavy Metal Accumulation and Bioindicator Potential

The potential of Bougainvillea spectabilis to accumulate atmospheric heavy metals was persuasively demonstrated by Dela Cruz *et al.* (2013) in Metro Manila, where leaves harvested from plants growing in the heavily trafficked Ermita district showed lead concentrations more than three-fold higher than those from the comparatively cleaner Las Piñas suburb over a nine-month period. Foliar Pb concentrations ranged from 0.006 to 0.387 ppm, with accumulation increasing progressively through the monitoring period in the polluted zone — a trajectory consistent with combined foliar absorption and root-to-shoot translocation. Cadmium accumulation (0.15–0.42 ppm) along urban roadsides has been similarly documented (Zou *et al.,* 2025). These findings mirror the heavy metal bio-concentration patterns observed in related ornamental species at ICAR-IARI, where wastewater-irrigated turf grasses and marigold accumulated Pb, Cd, and Zn proportional to external exposure levels, indicating consistent mechanisms of uptake across ornamental taxa (Balaji *et al.,* 2025; Vignesh *et al.,* 2023).

Practical Advantages in urban deployment

From a horticultural management standpoint, Bougainvillea offers several attributes that facilitate large-scale urban deployment: (i) drought tolerance and capacity to thrive on minimal supplemental irrigation once established; (ii) adaptability to a wide pH range (5.5–7.5) and varied soil textures; (iii) rapid extension growth enabling establishment of dense canopies within two to three seasons; (iv) versatility as a climber, hedge, standards, or espalier, permitting its integration into diverse street furniture and architectural contexts; and (v) prolific flowering that sustains ornamental value year-round in warm climates (Gilman, 1999; Jain *et al.,* 2019). These traits collectively lower the cost per unit phytoremediation benefit, making Bougainvillea an economically attractive component of municipal greening budgets.

Metropolitan Case Studies

Delhi, India

Delhi epitomises the intersection of rapid metropolitan growth and severe air quality degradation. The capital city consistently records $PM_{2.5}$ levels several multiples above the national ambient air quality standards, particularly during post-monsoon and winter months when thermal inversions trap vehicular and crop-burning emissions (Chowdhury *et al.,* 2018). Urban greening initiatives in Delhi have explored the establishment of dense multi-layered road green belts along arterial roads as a first line of defence against traffic-related pollution. Research has emphasised the critical importance of selecting native and naturalized species tolerant to high pollution loads, with the potential to provide year-round canopy cover (Joshi and Swami, 2009). Scientists at ICAR-IARI, New Delhi located within the Delhi metropolitan area, have actively contributed to this knowledge base through studies on indoor plant-mediated phytoremediation and urban landscape design (Tiwari *et al.,* 2019a; Singh *et al.,* 2019), providing regionally relevant recommendations grounded in experimental evidence.

Metro Manila, the Philippines

The Metro Manila experience with Bougainvillea as a heavy metal bioindicator and phytoremediator offers compelling field-level evidence of the genus's capabilities. A study by Dela Cruz *et al.* (2013) comparing foliar lead accumulation in Bougainvillea spectabilis growing in two contrasting districts confirmed progressive, dose-dependent accumulation of Pb in leaf tissue — a behaviour that mirrors observations in ornamental species under experimental metal-spiked wastewater irrigation conducted in India (Vignesh *et al.,* 2023; Verma *et al.,* 2023). These parallel findings across geographies reinforce the universality of foliar metal accumulation mechanisms and support the use of Bougainvillea as a standardised bioindicator for mapping urban lead pollution gradients.

Beijing, China

Beijing's large-scale urban forestry programme, which targeted $PM_{2.5}$ reduction as a primary ecosystem service outcome, demonstrated that well-designed urban vegetation patches significantly attenuate near-ground particulate concentrations while simultaneously moderating urban heat island intensity (Yang *et al.,* 2005). The use of wetland macrophytes as biofilters for inhalable particles in Beijing parks further expanded the toolkit of phytoremediative plant types available to urban planners (Wu and Yu, 2018). These findings corroborate the broader scientific consensus that diverse, structurally complex urban green infrastructure delivers superior and more resilient air quality benefits than monospecific plantings.

Mumbai, India

Mumbai's unique coastal geography introduces marine aerosols, high humidity, and sea salt particles into an already complex urban pollution mix. Studies evaluating dust capture efficiency along Mumbai roadsides identified species-specific variation in particle interception capacity and informed recommendations for species-appropriate roadside planting schemes (Joshi and Chauhan, 2020). The insights from Mumbai are particularly instructive for other coastal megacities in South and South-East Asia where Bougainvillea is widely naturalized and already present as a dominant roadside shrub, enabling its opportunistic incorporation into formalized phytoremediation programmes with minimal additional establishment cost.

Green Infrastructure Design for Maximum Phytoremediation Benefit

Translating the phytoremediation potential of individual species into measurable improvements in ambient air quality at the citywide scale demands careful attention to planting design, species assemblage, and spatial configuration. Road green belts (RGBs) positioned on both margins of arterial roads act as physical barriers, deflecting the pollution plume from the emission zone (vehicle lane) towards the vegetation canopy where particles are deposited and gases are absorbed (Abhijith *et al.,* 2017). Multi-layered belts — combining a taller tree canopy layer with a mid-height shrub tier and a ground-level herbaceous layer — create a more tortuous flow path for polluted air, increasing residence time within the vegetated zone and improving removal efficiency. Bougainvillea, growing as a dense thorny shrub or trained climber, is well suited to the mid-height and vertical surface tiers of such multi-layered configurations.

Vertical greening systems (VGS) — green walls and vegetated facades — represent an innovative solution for hyper-dense urban areas where horizontal ground space is at a premium. VGS can be retrofitted to building exteriors, transforming impervious surfaces into active phytoremediation interfaces while also providing thermal insulation benefits that reduce building energy demand (Perini and Rosasco, 2013). The vigorous climbing habit of Bougainvillea, combined with its xeric tolerance, makes it an ideal candidate for self-clinging or trellis-supported vertical green systems in semi-arid and sub-humid urban climates.

CHALLENGES AND FUTURE PERSPECTIVES

Despite the considerable scientific evidence supporting ornamental phytoremediation, several challenges constrain its wider application. At the street-canyon scale, dense low-level vegetation can impede turbulent mixing, paradoxically elevating pedestrian-level pollutant concentrations by reducing vertical dilution (Janhäll, 2015). Optimal green belt height-to-width ratios and canopy porosity parameters must therefore be defined through computational fluid dynamics modelling informed by field measurements in order to avoid inadvertent aggravation of pollutant hot spots.

The seasonality of deciduous species introduces temporal gaps in phytoremediation coverage, a concern particularly relevant in north Indian cities where winter pollution peaks coincide with leafless conditions in many exotic deciduous ornamentals. Bougainvillea's near-evergreen phenology in tropical and warm sub-tropical climates addresses this concern effectively. The saturation of leaf surfaces by heavy particle loads can diminish incremental deposition efficiency, underscoring the value of regular pruning as a management intervention that physically removes contaminated biomass and stimulates fresh foliage growth (Beckett *et al.,* 2000).

Research priorities for the next decade should include: (i) standardised, real-world quantification of phytoremediation fluxes for Bougainvillea and other key ornamentals under Indian meteorological and pollution regimes; (ii) development of composite species selection matrices that weight APTI, growth habit, maintenance intensity, and water requirement against pollutant removal efficiency; (iii) long-term monitoring of soil metal accumulation under roadside ornamental plantings to assess secondary contamination risks, building on existing expertise in heavy metal dynamics in ornamental crop systems (Balaji *et al.,* 2025; Verma *et al.,* 2023; Vignesh *et al.,* 2023); and (iv) integration of phytoremediation planning into smart city digital twins, coupling real-time air quality sensor networks with predictive vegetation performance models.

CONCLUSION

Urban air pollution stands as one of the defining environmental health crises of the twenty-first century, demanding solutions that are simultaneously effective, equitable, and enduring. Phytoremediation through carefully selected ornamental plants offers precisely this — a nature-based approach that converts urban green spaces from passive amenities into active air quality infrastructure. This review has demonstrated that ornamental plants deploy a sophisticated repertoire of physical and biochemical mechanisms to intercept particles and metabolise gaseous pollutants, and that the APTI provides a practical screening framework for matching species to pollution exposure contexts. Within this framework, Bougainvillea occupies a position of particular merit — combining established horticultural tractability, as evidenced by quality seedling production protocols developed at ICAR-IARI (Jain *et al.,* 2019), with documented tolerance and accumulation capacity for PM, NO_2, lead, and cadmium. Case studies from Delhi, Mumbai, Manila, and Beijing validate the real-world relevance of green infrastructure for ambient air quality improvement. Overcoming residual design and knowledge gaps through targeted research — including long-term field studies on heavy metal dynamics under ornamental plantings (Balaji *et al.,* 2025; Vignesh *et al.,* 2023; Verma *et al.,* 2023), plant stress physiology (Vanlalruati *et al.,* 2021, 2023), and urban landscape design (Singh *et al.,* 2019; Jain *et al.,* 2020) — will accelerate the transition from scientific demonstration to policy-embedded practice. With sustained institutional commitment, ornamental phytoremediation can meaningfully contribute to building cities that are not merely liveable but regenerative.

ACKNOWLEDGEMENTS

The authors are grateful to the Director, ICAR-Indian Agricultural Research Institute, New Delhi, for providing necessary facilities and support. The authors acknowledge the funding support received from ICAR, DBT, and DST for various research projects that contributed to the development of ideas presented in this review. Thanks are also due to the research scholars and technical staff of the Division of Floriculture and Landscaping, ICAR-IARI, for their dedicated contributions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

A.K. Tiwari: Conceptualization, Writing – original draft, Supervision, Review & editing. B. Singh: Writing – original draft, Data curation. Ritu Jain: Writing – review & editing, Resources. M.K. Singh: Writing – review & editing, Visualization. All authors have read the manuscript and agreed to its content. They have also approved the final version of the manuscript and consent to its submission.

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Current Horticulture 14(3): 42-44, July–September 2026
DOI: 10.5958/2455-7560.2026.00036.1
Received: 15 June 2026; Revised: 4 July 2026: Accepted: 3 September 2026

Research Article

Response of growth regulating chemicals on branching and early canopy development in mango (*Mangifera indica*)

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Abstract

An experiment was conducted to enhance early canopy formation and precocity in mango (Mangifera indica L.), involving treating of grafted saplings with PBZ, TIBA, 6-BAP and tip pinching for hastening bearing and induction of early branching for quick canopy formation. The results showed that plant height, stem girth, number leaves and primary laterals were found non-significant in mango Dashehari, however, maximum number of primary laterals (3.67) was noted in T_8 (pinching 5 cm) and maximum chlorophyll 'a' (1.89 mg/100 g) and total chlorophyll content (2.26 mg/100 g) were recorded in T_7. Similarly in Amrapali, maximum number of leaves (61.00) and highest number of primary laterals/plant (5.00) were noticed under treatment T_8 (pinching 5 cm removing shoot apex). In Chausa, highest number of leaves (56.68) and maximum number of primary laterals (5.00) were recorded in treatment T_8 (pinching 5 cm) and minimum number of leaves/ plant (31.00) and number of primary laterals (2.00) was recorded in T_2 (6-BAP 100 ppm) and T_7 (PBZ1500 ppm) respectively.

Key words: Branching, Canopy development, Juvenility, Hormones, Pinching, Branching

Mango (*Mangifera indica* L.) is commercially most important fruit crop in India. Uttar Pradesh holds the largest share of mango production in India, accounting for approximately 23.58-25.76% of the total, with the specific percentage varying by reporting period. Juvenility in mango, characterized by an extended non-fruiting vegetative phase, poses a major challenge in commercial fruit production. Young mango trees may take 5-7 years before transitioning into the reproductive stage, during the period orchardists incur continuous expenses on irrigation, nutrition, disease and pest control, and canopy development and management without any financial gain. Production of branched nursery plants is a critical operation for quality planting material production and its potential to bring higher and earlier yield, after planting (Van Oosten, 1978; Sadowski *et al.* 2007). A good root system, strong stem, well-developed crown with abundant number of laterals are criteria for quality nursery plants.

Growers required such trees for orchard establishment (Preston, 1968). Helail and Eissa (1997) recorded that spray of Paclobutrazole or TIBA along with root shortening and stem pinching were found most effective treatment in enhancing root and shoot branching and improved growth parameters. Islam *et al.* (2006) reported that grafted mango planted at 0.75-1 m distance in hedgerow system along with pruning and pinching during February produced the abundant laterals for scion growth. For encouraging laterals by altering apical dominance, several methods have been used, the most reliable is pinching and pruning of youngest leaves; keeping desired conical tree shape and wide crotch angle of feathers (Wertheim, 1978; Van den Berg 2003). However, mechanical pinching is labor intensive Job (Volz *et al.* 1994; Jung and Lee 2008). By modifying hormonal balance within the plant, growth regulators can help optimize canopy shape and improve the overall efficiency of light use, which ultimately contributes to higher productivity. Hence an experiment was conducted on enhance early canopy development in mango.

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MATERIALS AND METHODS

The investigation was carried out during 2023-2024 at ICAR-Central Institute for Subtropical Horticulture, Lucknow (Uttar Pradesh), India, representing subtropical climate located at 26° 51' 0.0000'' N and 80° 56' 59.9892'' E , annual rainfall 750-800 mm. The soil is coarse sandy loam, clay content 1.6-3.1% and pH ranging 7.75. Freshly grafted mango plants were taken (6-7 months after grafting) for laying out experiment, involving 04 varieties *i.e.* Dashehari (V_1), Amrapali (V_2) and Chausa (V_3) and separately treated with different concentration of T_1, T_2, 6-Benzaylaminopurines 800 & 1000 ppm, T_3, T_4-TIBA 125, 150 ppm, (Tri Iodo Benzoic Acid), T_5, T_6, T_7- pacloburazol (PBZ) 1500, 2000 & 2500 ppm, T_8-Pinching of apical portion of shoots 5 cm, T_9- 10 cm respectively and T_{10} – control (plain water spray). Containers (30 × 30 cm) of black in color of 400 gauge thickness were taken and filled with growing media comprising garden soil FYM, vermi-compost, neem cake, bonemeal and leaf mould (50% soil, 25% FYM, 10 % each vermi compost and bonemeal and 5% leaf mould) and filled in containers for raising the mango

Table.1: Effect of plant bio-regulators and pinching of grafted mango seedlings on lateral induction and chlorophyll contents Dashehari mango.

Treatment	Tree height (cm)	Trunk dia. (mm)	No. of leaves/ plant	No. of primary laterals	Chlorophyll 'a' mg/ 100 g	Chlorophyll 'b' mg/ 100 g	Total chlorophyll mg/ 100 g
T_1	72.37	16.93	30.67	1.67	0.93	0.28	1.27
T_2	59.38	20.01	34.00	3.33	0.93	0.33	1.27
T_3	65.7	22.84	34.00	3.00	1.63	0.47	2.06
T_4	78.35	23.48	28.33	4.00	1.69	0.53	2.19
T_5	73.37	18.89	36.67	3.33	0.86	0.36	1.23
T_6	86.07	23.13	31.67	1.67	1.43	0.46	1.87
T_7	71.39	20.77	46.00	3.33	1.89	0.37	2.26
T_8	65.77	18.08	42.67	3.67	1.75	0.44	2.19
T_9	72.03	18.45	50.00	3.33	1.56	0.43	1.99
T_{10}	86.37	16.14	34.33	1.33	0.93	0.33	1.26
C.D. (p=0.05)	**NS**	**NS**	**NS**	**NS**	**0.15**	**0.14**	**0.2**
SE(d)	**10.58**	**2.85**	**9.78**	**1.3**	**0.07**	**0.05**	**0.09**
C.V.	**17.62**	**17.29**	**32.56**	**55.44**	**6.45**	**15.32**	**6.61**

T_1, T_2, 6-Benzaylaminopurines 800 & 1000 ppm, T_3, T_4-TIBA 125, 150 ppm, (Tri Iodo Benzoic Acid), T_5, T_6, T_7- Paclouburazol (PBZ) 1500, 2000& 2500 ppm, T_8-Pinching of apical portion of shoots 5 cm, T_9- 10 cm respectively and T_{10} – Control

Table. 2: Effect of plant bio-regulators and pinching of grafted mango seedlings on lateral induction and chlorophyll contents of Amrapali

Treatment	Plant height (cm)	Stem dia. (mm)	No. of leaves/ plant	No. of primary laterals	Chlorophyll 'a' mg/ 100 g	Chlorophyll 'b' mg/ 100 g	Total chlorophyll mg/ 100 g
T_1	93.69	24.57	50.33	3.33	1.75	0.38	2.14
T_2	96.37	18.9	41.68	3.67	1.71	0.27	1.98
T_3	96.68	20.77	24.33	2.33	1.46	0.31	1.77
T_4	95.37	21.33	47.00	4.67	1.47	0.34	1.81
T_5	86.07	26.27	39.68	2.67	1.41	0.34	1.75
T_6	83.02	22.57	45.00	3.67	1.39	0.34	1.7
T_7	95.38	21.3	30.00	1.00	1.44	0.3	1.74
T_8	86.7	20.93	61.00	5.00	0.9	0.33	1.22
T_9	88.05	22.07	38.33	3.67	0.97	0.25	1.22
T_{10}	82.36	23.7	42.68	2.67	0.65	0.25	0.88
C.D. (p=0.05)	**NS**	**NS**	**13.06**	**1.84**	**0.12**	**NS**	**0.15**
SE(d)	**11.17**	**2.89**	**6.17**	**0.87**	**0.05**	**0.05**	**0.07**
C.V.	**15.19**	**15.91**	**17.99**	**32.64**	**5.07**	**22.27**	**5.29**

plants. BAP and TIBA was dissolved in 1N sodium chloride and final volume was made with adding distilled water, The ethenol was used for dissolving the Paclobutrazol (PBZ) and final concentration was made adding distilled water. Five plants each were taken per replication for spraying of growth regulating hormones and each spray were carried in the mid- May and again in September. To avoid the drifting of chemicals from one treatment to other treatment polythene sheet was spread around the rows of the plants and each time the polythene sheet was washed with fresh water before use in next treatments. The pinching treatment was carried out by removing 5 cm and 10 cm apical portion in each variety during mid-June. The experiment was carried out in randomized block design with three replications. Observations on plant height was recorded with measuring tape in cm, stem girth 5 cm above union was recorded with the help of digital vernier caliper of model Mitutoyo Digital Vernier Caliper 0-150 mm 500-196 , no of primary branches and no of leaves were counted from 5 treated plants of each replications. The experiments were laid out in randomized block design with 3 replications. Data recorded in triplicate and analyzed using OP stat software of HAU, Hisar, Haryana.

RESULTS AND DISCUSSION

The maximum plant height (86.37 cm) was in treatment T_{10} (untreated plants). However, effect of treatments on plant height, stem girth, number of leaves/ plant and number of primary laterals were not found significant. Although, maximum laterals were recorded (3.67) in T_8 (pinching 5 cm from tip). The maximum chlorophyll 'a' (1.89 mg/ 100 g) was noted in treatment T_7 (PBZ 2500 ppm). Similarly

Table. 3: Effect of PGR chemicals and pinching of grafted mango seedlings on lateral induction and chlorophyll contents of plants variety Chausa.

Treatment	Tree height (cm)	Trunk dia. (mm)	No. of leaf/ plant	No. of primary laterals	Chlorophyll 'a' mg/ 100 g	Chlorophyll 'b' mg/ 100 g	Total chlorophyll mg/ 100 g
T_1	61.74	18.61	31.68	3.00	1.44	0.36	1.80
T_2	98.94	22.73	31.00	4.00	1.68	0.33	2.03
T_3	81.04	19.45	34.68	3.33	1.46	0.38	1.84
T_4	77.39	22.98	43.68	3.00	1.20	0.26	1.49
T_5	62.01	23.00	35.68	2.33	0.87	0.32	1.19
T_6	66.69	22.78	34.00	2.33	0.83	0.25	1.08
T_7	67.38	22.50	37.68	2.00	1.04	0.33	1.34
T_8	71.73	23.04	56.68	5.00	1.82	0.26	2.08
T_9	89.36	27.40	47.00	4.00	1.79	0.31	2.10
T_{10}	79.35	19.37	29.00	1.33	0.90	0.33	1.23
C.D. (p=0.05)	NS	NS	14.27	1.84	0.18	NS	0.14
SE(d)	12.42	2.32	6.74	0.85	0.08	0.05	0.065
C.V.	20.13	12.78	21.66	34.41	8.12	20.78	4.95

highest chlorophyll 'b' (0.53 mg/100g) was noticed in treatment T_4, followed by in T_3 (0.47 mg/100g) and T_6 (0.46 mg/100g). Maximum total chlorophyll content (2.26 mg/100 g) was recorded in T_7, followed by (2.19 mg/ 100 g) in T_4 and T_8.

The plant height and stem girth were not found significant in Amrapali. While maximum number of leaves plant (61.00) was recorded in treatment T_8 (pinching 5 cm), followed by treatment T_1 (50.33) and T_4 (47.00) respectively. The number of primary laterals which was maximum (5.00) in treatment T_8 (pinching 5 cm), followed by 4.67 in T_4 (PBZ 2000 ppm). The data showed that highest amount of chlorophyll 'a' (1.75 mg/100g) was noticed in treatment T_1 (BAP 800 ppm), followed by 1.71 in T_2 (BAP 1000 ppm), whereas the lowest chlorophyll 'a' content 0.65 mg/100 g was noticed in T_{10} (control). Similarly, highest total chlorophyll content (2.14 mg/100 g) was noticed in T_1 followed by T_2, *i.e.* 1.98 mg/100 g while minimum total chlorophyll content (0.88 mg/100 g) was recorded in T_{10}. However, effect of hormones on chlorophyll 'b' was found non-significant.

Similarly, in Chausa variety, different treatment effects on plant height, stem girth and chlorophyll 'b' were found non-significant. Whereas maximum number of leaves plant (56.68) and maximum number of primary laterals (5.00) were recorded in T_8 (pinching 5 cm) while minimum number of leaves (29.00) and number of primary laterals (1.34) were noticed in T_{10} (control). Similarly highest chlorophyll 'a' (1.82 mg/100 g) was recorded under T_8 and lowest in T_6 (0.83). Total chlorophyll content was recorded (2.08 mg/100 g) was under treatment T_8 (pinching 5 cm), while the minimum total chlorophyll (1.08 mg/100 g) was noticed in treatment T_6.

CONCLUSION

The findings indicated that shoot pinching is an effective practice for promoting early canopy development and improving precocity in grafted mango plants. The process shortens the pre-bearing duration, and early and balanced canopy development.

ACKNOWLEDGEMENTS

Authors are duly thankful to Uttar Pradesh Council of Science and Technology for providing financial support to carry out present experiment.

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Current Horticulture 14(3): 45-49, July–September 2026
DOI: 10.5958/2455-7560.2026.00037.3
Received: 19 January 2026; Revised: 9 July 2026: Accepted: 3 September 2026

Research Article

Integrated farming system in improving production, productivity and livelihood security

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Abstract

A three-year field experiment (2021-2024) was conducted at the ICAR-Indian Institute of Farming Systems Research, Meerut, Uttar Pradesh, to evaluate horticulture-based integrated farming system models. Four systems including mango (*Mangifera indica* L.) + tomato (*Solanum lycopersicum* L.) + dairy; papaya (*Carica papaya* L.) + beekeeping + aloe vera (*Aloe barbadensis* miller); pomegranate (*Punica granatum* L.) + drumstick + goat farming; and aonla (*Emblica officinalis* Gaertn) + beekeeping + agroforestry were assessed using a randomized block design for crop productivity, economic returns, benefit: cost ratio (BCR), soil fertility, and resource-use efficiency. All IFS models significantly outperformed conventional single-enterprise systems in yield, profitability, and soil health. Mango + tomato + dairy system achieved the highest vegetable yield (34.5 t ha^{-1}), while papaya + beekeeping + Aloe vera system recorded the highest fruit yield (12.30 t ha^{-1}), net return (₹1,60,000 ha^{-1}), and BCR (2.30). Integrated systems markedly increased soil organic carbon (up to 0.91%) and improved available nitrogen, phosphorus, and potassium through efficient recycling of crop residues and livestock byproducts. Agroforestry- and beekeeping-based systems further enhanced soil moisture retention, nutrient conservation, and system resilience. Overall, horticulture-based IFS models offer a robust pathway for sustainable intensification, income diversification, and climate resilience for smallholder farmers.

Key words: Integrated Farming System, Small and marginal farmers, Crop Productivity, Sustainability, Benefit: cost ratio

Integrated Farming Systems (IFS) is a structured and viable development model, particularly well-suited to small and marginal holdings, and is often more feasible and profitable than mono-cropping or large-scale specialized farming systems (Ravisankar *et al.,* 2007; Bhagat *et al.,* 2025). By diversifying farm enterprises, IFS reduces farmers' dependence on a single source of income and distributes risk across multiple components. Integrated Farming Systems promotes crop diversification, enhances soil quality, supports agro-ecological balance and improves pest and disease management (Paramesh *et al.,* 2020; Kumar *et al.,* 2025). It integrates a range of agricultural activities, including crop cultivation, livestock rearing, aquaculture, poultry, beekeeping and horticulture, to optimize resource use while maintaining ecological stability (Kumar *et al.,* 2012). Consequently, IFS is considered economically viable, environmentally sustainable, and socially acceptable (Gill *et al.,* 2009; Biswas *et al.,* 2013). However, a major challenge remains in identifying the optimal combination of crops, livestock, and aquatic components to maximize economic returns while enhancing ecosystem services (Dumont *et al.,* 2013; Bhagat *et al.,* 2024).

The climate of India presents unique agricultural challenges. Despite the region's fertile land and water resources, productivity remains low, and many farms focus on subsistence agriculture also farmers in this region face recurring issues such as unpredictable climatic conditions and low productivity of crops. Traditional mono-culture practices, coupled with resource in-efficiencies, have limited the potential of smallholder farmers. The IFS aims to mitigate these issues by exploiting a diversified and synergistic farming model that maximizes resource utilization, supports ecological health, and strengthens farm income. Keeping its importance about IFS programme we have evaluated the potential of IFS model to address the agricultural challenges. Therefore, study was carried out to provide insights into how IFS can enhance agricultural resilience, double farmers' income, ensuring food, maintaining ecological balance, providing employment opportunities and ecological sustainability.

MATERIALS AND METHODS

An IFS model was conducted at ICAR-Indian Institute of Farming Systems Research, Meerut, Uttar Pradesh, during 2021-24. The experimental site lies between latitudes 26°04′ and 30°21′ N and longitudes 77°03′ and 80°04′ E, at an elevation of 237 m above mean sea-level. The region receives an average annual rainfall of about 650 mm, which is erratic, uncertain, and unevenly distributed across the year. Nearly 80% of the total precipitation occurs during the monsoon period from June to September. Prolonged dry spells are common during the winter season. The soils under

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various cropping sequences were classified as clay loam, with medium available nitrogen (320 kg ha^{-1}), high available phosphorus (46 kg ha^{-1}), and medium available potassium (126 kg ha^{-1}). Soil reaction was slightly alkaline (pH 7.8) and contained adequate levels of micronutrients, including manganese (7.0 mg kg^{-1} DTPA), zinc (1.5 mg kg^{-1} DTPA), iron (15.0 mg kg^{-1} DTPA), and copper (2.5 mg kg^{-1} DTPA), along with a microbial biomass carbon content of 380 mg g^{-1} soil. The initial organic carbon content of the surface soil (0-30 cm depth) was recorded as 0.45%.

The four horticulture-based IFS models were evaluated: (i) fruit and vegetable cultivation integrated with dairy farming (mango + tomato + dairy which includes 2 murrah buffaloes and 1 gir cow) (ii) Agro-forestry combined with beekeeping and medicinal crop cultivation (papaya + beekeeping + aloe vera); (iii) Perennial fruit-based systems integrated with poultry farming and vermicomposting (pomegranate + poultry + vermicompost); and (iv) rainfed horticulture integrated with goat farming and organic nutrient management (drumstick + goat farming + green manure). An on-farm participatory approach was employed to evaluate these horticulture-based IFS models. Livestock enterprises including dairy, poultry, goats, and beekeeping were incorporated to support horticultural production and provide diversified income streams. Agroforestry components such as fruit trees, shade trees, and windbreaks were established through alley cropping arrangements.

Perennial horticultural crops such as mango, papaya, and pomegranate generated stable, long-term returns, while short-duration crops like tomato ensured regular cash flow. Livestock components provided continuous income and organic nutrient sources, enhancing nutrient cycling and soil health, while beekeeping improved pollination services and generated additional income. Poultry and goat farming offered rapid returns, effectively utilized crop residues, and strengthened organic nutrient management, thereby improving system resilience to climate variability, particularly under rainfed conditions.

Data were collected across multiple cropping seasons. Parameters assessed included crop productivity, net returns, benefit: cost ratio, nutrients and soil health indicators such as organic carbon content. The data were subjected to statistical analysis using a randomized block design.

RESULTS AND DISCUSSION

Crop productivity

The productivity of horticultural crops under different integrated farming system (IFS) models is presented in Table 1. All IFS treatments recorded higher crop yields, demonstrating the beneficial interactions among system components such as livestock, beekeeping, and agroforestry. Improved nutrient cycling through organic residue incorporation, enhanced soil moisture conservation and favourable microclimatic conditions collectively contributed to superior crop performance.

Mango + tomato + dairy system produced highest vegetable (tomato) yield (34.5 t ha^{-1}), highlighting the positive effects of dairy-derived organic inputs and efficient water management. This system also recorded a fruit yield of 9.20 t ha^{-1}, reflecting the successful integration of perennial fruit crops with annual vegetables. The papaya + beekeeping + aloe vera model achieved the highest fruit productivity (12.30 t ha^{-1}) along with a medicinal crop yield of 6.7 t ha^{-1}. Enhanced pollination services from beekeeping and efficient land use through Aloe vera cultivation significantly contributed to increased system productivity and income diversification. Similarly, the aonla + beekeeping + agroforestry system resulted in higher fruit (8.90 t ha^{-1}) and medicinal crop yields (5.2 t ha^{-1}), largely due to improved soil moisture retention and nutrient dynamics under agroforestry conditions. In contrast, pomegranate + drumstick + goat farming system recorded moderate fruit (7.80 t ha^{-1}) and vegetable yields (21.40 t ha^{-1}). Although yields were comparatively lower, the inclusion of goat farming enhanced nutrient recycling through manure application, thereby supporting long-term system sustainability.

A crop-horticulture-livestock based IFS evaluated over 11 years in Telangana achieved an average productivity of 31.42 t ha^{-1} with a cost of production of ₹3,13,179. The system generated gross and net annual returns of ₹4,96,302 and ₹1,83,123, respectively, with livestock (59.07%) and cropping units (33.06%) contributing substantially to overall productivity (Ramana *et al.,* 2024). Shyam *et al.* (2023) and Kumari *et al.* (2022) emphasized that synergistic integration of enterprises and efficient recycling of by-products enhance system self-

Table 1: Performance of horticultural crops in different IFS models

IFS model	Fruit crop (t/ha)	Vegetable crop (t/ha)	Medicinal/ aromatic plants (t/ha)
Mango + tomato + dairy	9.20	34.50	
Papaya + beekeeping + Aloe vera	12.30	-	6.7
Pomegranate + drumstick + goat farming	7.80	21.40	
Aonla + beekeeping + agroforestry	8.90	-	5.2

Table 2: Economic performance of different IFS models

IFS model	Gross income (₹/ha)	Net profit (₹/ha)	BCR (benefit:cost ratio)
Mango + tomato + dairy	2,50,000	1,40,000	2.25
Papaya + beekeeping + Aloe vera	2,80,000	1,60,000	2.30
Pomegranate + drumstick + goat farming	2,10,000	1,10,000	2.00
Aonla + beekeeping + agroforestry	2,00,000	1,05,000	1.98

Table 3: Soil health improvement under different IFS models

IFS model	Soil organic carbon (%)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
Mango + tomato + dairy	0.86	347	48	290
Papaya + beekeeping + Aloe vera	0.91	340	51	305
Pomegranate + drumstick + goat farming	0.80	365	49	260
Aonla + beekeeping + agroforestry	0.85	356	53	285

sufficiency by converting waste into valuable inputs, thereby improving productivity and sustainability indices. The enhanced profitability of IFS is primarily attributed to effective byproduct recycling, which reduces production costs, and product diversification, which minimizes risk by compensating losses in one enterprise with gains in others. In the present system, although the dairy component incurred losses, overall net income remained high due to superior performance of crop + goat + poultry unit. Paramesh *et al.* (2022) reported that IFS can increase farm profitability by up to 265% compared to single-enterprise systems through substantial gains in net returns. Overall, these findings clearly demonstrate that horticulture-based IFS models outperform mono-enterprise systems in terms of crop productivity, profitability, and long-term sustainability, particularly when livestock and pollinator components are effectively integrated.

Economic performance

All systems proved economically viable, with benefit: cost (BC) ratios ranging from 1.98 to 2.30, indicating efficient resource utilization under integrated farming (Table 2). The papaya + beekeeping + aloe vera system achieved the highest net return (₹1,60,000 ha^{-1}) and BC ratio (2.30), owing to diversified income from fruit production, medicinal crops, and honey bee, along with relatively lower operational costs. Mango + tomato + dairy system also demonstrated high profitability, recording a net return of ₹1,40,000 ha^{-1} and a BC ratio of 2.25, supported by regular income from vegetables and dairy enterprises and effective recycling of farm residues. The pomegranate + drumstick + goat farming and aonla + beekeeping + agroforestry systems yielded net returns of ₹1,10,000 ha^{-1} and ₹1,05,000 ha^{-1}, respectively. Slightly lower BC ratio values in these systems may be attributed to higher initial investment and longer gestation periods of perennial components; however, they provide greater income stability and resilience under variable climatic conditions. Meena *et al.* (2022) reported that crop production incurred the highest costs, followed by dairy enterprises, primarily due to higher input requirements. Similarly, Singh and Riar (2014) observed that integrated systems such as crop + floriculture and crop + beekeeping were more productive and profitable than sole cropping, with net returns increasing by 29.53% and 19.09%, respectively.

Soil fertility and resource-use efficiency

Integrated farming practices significantly enhanced soil organic carbon (SOC) content and nutrient availability, indicating improved resource-use efficiency and long-term sustainability (Table 3). Papaya + beekeeping + Aloe vera system recorded highest SOC (0.91%), reflecting continuous organic matter addition and enhanced microbial activity. Similarly, mango + tomato + dairy system exhibited elevated SOC levels (0.86%), emphasizing the positive role of livestock-derived organic inputs in improving soil quality. Available nitrogen, phosphorus and potassium increased across all IFS models, with maximum values of 365 kg ha^{-1} (N), 53 kg ha^{-1} (P), and 305 kg ha^{-1} (K) observed in the papaya-based system.

Agroforestry-oriented systems, particularly aonla + beekeeping + agroforestry, further contributed to improved soil moisture retention, nutrient conservation, and long-term soil fertility. These findings are consistent with earlier studies (Kumar et al., 2012; Desai et al., 2013; Meena et al., 2019). Recycling of crop residues and farm byproducts under IFS played a crucial role in enhancing soil health by returning organic matter and nutrients to the soil, thereby reducing dependence on chemical fertilizers for crops and horticultural plants. The on-farm utilization of by products not only improved soil fertility but also reduced production costs, leading to increased farm profitability. Application of safe production practices (recommended FYM + fertilizer+

plant protection with organic methods) + IIHR microbial consortium @ 12.5 kg/ha for each of the crop are profitable alternatives of conventional practices in coriander cv. Mahak and radish cv. Ivory White system (Singh et al., 2025). Rice-blackgram-short-duration cassava was productive, profitable and energy efficient, besides maintaining soil health. The system will also help to diversify our food basket and achieve self-sufficiency in pulse production in India (Suja et al., 2025).

Intercropping cassava with vegetables can help improve nutritional yield per hectare. By enhancing soil health while maintaining yield levels, intercropping under organic management could provide a basis for sustainable agricultural policy, contribute to climate resilience planning, nutrition-sensitive agriculture and food security in tropical regions (Nandan and Suja, 2026). The observed improvements in soil health parameters highlight the ecological and economic benefits of integrated farming systems in sustaining soil productivity while minimizing reliance on external chemical inputs. Overall our results clearly indicate that horticulture-based IFS improves crop yields, economic returns, and soil health. Strategic integration of horticultural crops with livestock, beekeeping, and agroforestry enhances resource recycling, promotes income diversification, and supports environmental sustainability.

CONCLUSION

The study demonstrates that horticulture-based IFS model offer a sustainable strategy to enhance income, employment, food and nutritional security. Papaya + Aloe Vera + beekeeping was the most profitable model (₹1,60,000 ha^{-1}; BC ratio 2.30), while mango + tomato + dairy achieved highest vegetable yield (34.5 t ha^{-1}) and improved soil fertility through organic nutrient recycling. The IFS consistently enhanced soil health, increasing organic carbon (0.65-0.78%), microbial activity, and moisture retention. Integration of crops, livestock, and allied enterprises promoted biodiversity, optimized resource use, reduced chemical inputs, and strengthened ecosystem resilience. Thus, horticulture-based IFS provide a transformative approach for smallholders, delivering higher, stable incomes, ecological sustainability, and resilience against climate and market fluctuations.

Declaration of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Current Horticulture 14(3): 50-55, July–September 2026

DOI: 10.5958/2455-7560.2026.00038.5

Research Article

Received: June 20, 2025; Revised: 20 February 2026: Accepted: 4 September 2026

Evaluation of seed priming effect on growth, seed yield and quality of cumin (*Cuminum cyminum*) under field and laboratory conditions

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Abstract

The cumin (*Cuminum cyminum* L.) varieties, Gujarat Cumin-2 (GC-2) and Gujarat Cumin-4 (GC-4) were subjected to four different priming treatments, *viz.* IAA (100 ppm), GA_3 (200 ppm), cytokinin (100 ppm), and KH_2PO_4 (3%), along with an untreated control, at B. A. College of Agriculture, AAU, Anand (Gujarat). The field experiment was conducted in a randomized block design (factorial), while laboratory evaluation was carried out using a completely randomized design (factorial). The results revealed that the interaction between priming treatments and varieties significantly influenced growth, seed yield, and quality attributes. Variety GC-4 was significantly superior to GC-2 in terms of field emergence and growth, whereas GC-2 exhibited significantly better seed quality parameters under laboratory conditions. Among the priming treatments, GA_3 enhanced seed yield and growth performance under field conditions, while KH_2PO_4 proved most effective in improving seed quality under laboratory evaluation.

Key words: Priming treatments, Growth hormones, Seed quality, Seed yield

Cumin (*Cuminum cyminum* L.), belonging to the family Apiaceae (Umbelliferae) is extensively cultivated in India, Iran, Morocco, Turkey, Egypt, and Argentina. Farmers often encounter problems related to poor seed germination, weak seedling establishment, uneven crop growth, and susceptibility to pests and diseases. Seed priming has emerged as a promising technology to overcome these constraints.

This technique involves controlled pre-hydration treatments such as halo-priming, hydro-priming, osmo-priming, and nano-priming, that activate pre-germinative metabolic processes, thereby enhancing germination, seedling vigour, stress tolerance, and crop performance (McDonald, 2000; Paparella *et al.,* 2015). Therefore, present investigation was undertaken to evaluate the effect of different seed priming treatments on seed germination, seedling growth, yield, quality of cumin under field and laboratory conditions.

MATERIALS AND METHODS

The field and laboratory experiments were conducted at B. A. College of Agriculture, AAU, Anand, to evaluate the effect of seed priming on seed quality, crop growth, and seed yield in cumin. Two cumin varieties (GC-2 and GC-4) were used. Seeds of both varieties were subjected to four priming treatments, *viz.* IAA (100 ppm), GA_3 (200 ppm), cytokinin (100 ppm), and KH_2PO_4 (3%), selected based on previous studies, along with an untreated control. The primed seeds were evaluated under both field and laboratory conditions. The field experiment was laid out in a factorial randomized block design with three replications, while the laboratory experiment was conducted in a factorial completely randomized design with three replications

Seeds were subjected to priming with IAA (100 ppm), GA_3 (200 ppm), cytokinin (100 ppm) and KH_2PO_4 (3%) for 8 hours. Seeds were soaked in priming solutions having double the volume of seed and ensured that seeds remained immersed in the solution, to avoid precocious germination during the treatment period. Seeds were dried back to the original moisture content under shade (Ghobadi *et al.,* 2012).

The observations on seed growth and yield parameters under field conditions, *viz.* field emergence (%), plant height (cm), number of umbels, number of seeds/umbel, number of seeds/plant, seed yield/plant (g), seed yield/plot (g), and 1,000-seed weight (g), were recorded following standard procedures. The observations on seed quality and physiological parameters under laboratory conditions, *viz.* germination (%), root length (cm), shoot length (cm), seedling length (cm), seedling fresh weight (mg), seedling dry weight (mg), seedling vigour index-I (length), and seedling vigour index-II (mass), were determined as per the ISTA Rules (2021).

The data were statistically analyzed by OPSTAT software for statistical procedures, Steel and Torrie (1960).

RESULTS AND DISCUSSION

Higher field emergence (65.60 %) was recorded by GC 4 compared to GC 2 (62.87 %). Significantly highest

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field emergence (76.50 %) was recorded by GA_3 (P_3) which was at par with KH_2PO_4 (P_5) (69.67 %) and control recorded significantly lowest field emergence (53.67 %). GC 4 primed with GA_3 showed higher field emergence (77.57 %), followed by GA_3 with GC 2 (75.71 %) and GC 2 in the control recorded lowest field emergence. The best result was found in GA_3, which is a growth promoting hormone. KH_2PO4, a commonly known chemical for promoting seed germination and their effect resulted in increased activity of total α-amylase and proteases in germinating seeds and improved proteins, RNA, DNA, free amino acid and soluble sugars during germination. The results confirmed to those of Hossein *et al.* (2012), Giannakoula *et al.* (2012), Gholami *et al.* (2013), Danesh-Talab *et al.* (2014), Trivedi *et al.* (2019).

The effect of varieties and priming treatments was significant, but interaction was non-significant. Significantly higher (36.67 cm) and lower (34.56 cm) plant height (36.67 cm) were recorded in GC 2 and GC 4, respectively. The significantly highest plant height was recorded by GA_3 (39.10 cm) which was at par with KH_2PO_4 (36.93) and significantly lowest observed with cytokinin (32.29 cm). GC 2 primed with GA_3 recorded highest plant height (40.25 cm), followed by GC 2 primed with KH_2PO_4 (38.43 cm) and lowest with cytokinin in GC 4 (32.21 cm). Primed seeds established earlier, Gibberellic Acid (GA_3) treatment increased photosynthetic activity, improved growth criteria, increased stem length, number of flowers/plant, fruit setting, and yield. Auxins also induced cell elongation and increased photosynthetic activities. The results are in accordance with those of Khalil *et al.* (2006), Hoque and Haque (2002), Verma and Sen (2008) and Danesh-Talab*et al.* (2014).

GC 4 and GC 2 recorded significantly higher (62.57) and lower (56.23) number of umbels/plant, respectively. The significantly highest number of umbels/plant (69.33) was recorded in $GA_{3,}$ followed by KH_2PO_4 (63.15) and significantly lowest (51.32) with the control.GC 4 primed with GA_3 recorded highest (70.05) number of umbels per plant followed by GC 2 primed with GA_3 (68.60) non-primed seeds ofGC 2 recorded lowest number of umbels (51.32).Pre-sowing and seed priming treatment promote seed germination and healthy seedling establishment by promoting water uptake, α-amylase activity, protease activity, solubilization of nitrogen from endosperm to growing embryonic axis. GA_3 priming resulted in enhanced photosynthetic activity, increased stem length, number of flowers per plant, and induced fruit setting (Shah, 2007 in black cumin). KH_2PO_4 priming attributed to early germination and vigourous growth, resulting in higher umbels in cumin. The results are in accordance with the studies of Shirzad *et al.* (2012) and Danesh-Talab*et al.* (2014).

Both GC 4 and GC 2 recorded significantly higher (24.70) and lower (20.84) number of seeds/ umbel, respectively. The highest number of seeds/umbel (27.00) was recorded by GA_3 which was at par with KH_2PO_4 (24.33) and lowest (19.08) with non-primed seeds. The highest number of seeds/umbel (28.95) was recorded by GC 4 primed with GA_3 followed by the same variety primed with KH_2PO_4 (25.96) and non-primed seeds of GC 2 had lowest (17.13) (Table 1). Priming accelerated imbibition, enabling the emergence phase and multiplication of radicle cells, leading to uniform crop stand establishment. The results are in accordance with those findings of Hoque and Haque (2002) and Danesh-Talab*et al.* (2014).

GC 4 and GC 2 recorded significantly higher (1563.65) and lower (1191.14) number of seeds/plant, respectively. The highest (1876.71) and lowest (986.87) number of seeds/plant were recorded by GA_3 and the control, respectively. The highest number of seeds/ plant (2032.21) was recorded by GC 4 primed with $GA_{3,}$ followed by GC 4 primed with KH_2PO_4 (1735.39) and lowest with non-primed seeds GC 2 (816.62). Priming treatments significantly influenced the number of seeds/plant during plant growth period, leading to better crop growth rate and net assimilation rate. GA_3 priming treatment improved assimilated area, enhancing photosyn thates in key plant parts, and regulating plant development. Primed seeds could achieve uniform germination due to stimulatory effects of priming at early stages of germination. Priming also accelerated imbibition, facilitating the emergence phase and the multiplication of radicle cells, enabling uniform crop stand establishment. The results are in accordance with previous findings of Hoque and Haque (2002) and Danesh-Talab*et al.* (2014).

The GC 4 and GC 2 recorded significantly higher (6.80 g) and lower (4.98 g) seed yield per plant, respectively. Significantly highest (8.09 g) and lowest (4.02 g) seed yield were recorded by GA_3 and the control, respectively. GC 4 primed with GA_3 recorded highest seed yield (9.15 g/ plant) and non-primed seeds of GC 2 recorded lowest (3.19 g/plant). The difference in seed yield between varieties is due to genotypic variation, which is positively correlated with seedling vigour (Archana and Joshi, 2016). Priming with GA_3 increased seed yield per plant due to increased plant growth and improved physiological efficiency. IAA inducing cell elongation and photosynthetic activities in plants also had beneficial effects on flower retention and lentil yield. These results are in accordance those findings of Shirzad *et al.* (2012), Ghassemi-Golezani *et al.* (2013), Yadav *et al.* (2025) and Danesh-Talab*et al.* (2014).

Table 1: Effects of priming treatments on growth and yield parameters

Treatment	Field emergence (%)	Plant height (cm)	Number of umbels/ plant	Number of seeds/ umbel	Number of seeds/ plant	Seed yield/ plant (g)	Seed yield/ plot (g)	1,000 seed weight (g)
Variety								
V_1	62.87	36.67	56.23	20.84	1191.14	4.98	286.87	4.29
V_2	65.60	34.56	62.57	24.70	1563.65	6.80	416.66	4.54
S.Em ±	1.52	0.56	1.42	0.69	31.39	0.16	6.97	0.08
CD at 5 %	NS	1.67	4.21	2.06	93.26	0.49	20.72	0.25
Treatment								
P_1	53.67	33.22	51.32	19.08	986.87	4.02	205.99	4.06
P_2	66.17	35.54	58.23	22.47	1322.01	5.79	326.45	4.34
P_3	76.50	39.10	69.33	27.00	1876.71	8.09	560.99	4.84
P_4	55.17	32.29	54.97	20.98	1156.57	4.94	242.80	4.24
P_5	69.67	36.93	63.15	24.33	1544.80	6.61	422.58	4.58
S.Em ±	2.41	0.89	2.24	1.10	49.63	0.26	11.03	0.13
CD at 5 %	7.15	2.64	6.65	3.26	147.46	0.77	32.77	0.39
Interaction								
V_1P_1	51.67	33.91	47.40	17.13	816.82	3.19	156.00	3.93
V_1P_2	64.34	36.41	54.16	20.67	1120.43	4.73	258.03	4.22
V_1P_3	75.71	40.25	68.60	25.06	1721.21	7.03	487.75	4.68
V_1P_4	53.32	34.38	50.83	18.67	943.01	3.90	177.49	4.13
V_1P_5	68.86	38.43	60.14	22.69	1354.22	6.07	355.06	4.48
V_2P_1	55.95	32.53	55.23	21.04	1156.92	4.84	255.97	4.19
V_2P_2	67.67	34.67	62.30	24.27	1523.59	6.85	394.88	4.46
V_2P_3	77.57	37.96	70.05	28.95	2032.21	9.15	634.25	4.99
V_2P_4	56.40	32.21	59.10	23.29	1370.13	5.98	308.12	4.36
V_2P_5	70.71	35.42	66.17	25.96	1735.39	7.15	490.09	4.68
GM	64.23	35.62	59.40	22.77	1377.39	5.89	351.76	4.41
S.Em ±	3.40	1.26	3.17	1.55	70.19	0.37	15.59	0.19
CD at 5 %	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	9.18	6.12	9.23	11.80	8.83	10.79	7.68	7.34

Variety: V_1: Gujarat Cumin 2 and V_2: Gujarat Cumin 4
Treatments: P_1: Control, P_2: IAA (Indole Acetic Acid, 100 ppm), P_3: GA_3 (Gibberellic Acid, 200 ppm), P_4: Cytokinin (100 ppm), P_5: KH_2PO_4 (3 %)

The GC 4 and GC 2 were recorded significantly higher (416.66 g) and lower (286.87 g) seed yield per plot, respectively. The significantly highest seed yield per plot (560.99 g) was recorded by GA_3 followed by KH_2PO_4 (422.58 g) and lowest by non-primed (205.99 g).GC 4 primed with GA_3 recorded highest seed yield per plot (634.25 g), followed by GC 4 primed with KH_2PO_4 (490.09 g) and unprimed seeds of GC 2 recorded lowest (156.00 g). Priming with GA_3 and KH_2PO_4 had best effect on seed yield per plant through improved photosynthesis capacity, synthesis of hydrolytic enzymes and ultimately resulting in highest crop yield. A positive correlation was also observed in number of effective umbels with respect to yield. Early plant establishment allowed for developmental stages like jointing, booting, anthesis and grain development. Improved leaf area duration and crop growth rate promoted dry matter accumulation, resulting in highest seeds per umbels and seed weight. The results are in accordance with the findings of Shah (2007), Gholami *et al.* (2013) and Danesh-Talab *et al.* (2014).

The highest 1,000 seeds weight (4.84 g) was recorded by GA_3, which was at par with KH_2PO_4 (4.58 g) and significantly lowest with non-primed seeds (4.06g).GC 4 primed with GA_3 recorded highest (4.99 g), followed by GC 2 primed with same treatment (4.68 g) and lowest with unprimed seeds of GC 2 (3.93 g).Seed size and quality influence crop establishment, yield components, and seed yield. Priming modulates ions uptake and hormones homeostasis, leading to increased plant growth and cell division. The results are in accordance with those of Shirzad *et al.* (2012), Gholami *et al.* (2013) and Danesh-Talab *et al.* (2014).

The GC 2 and GC 4 recorded significantly higher (86.27 %) and lower (83.93 %) germination, respectively (Table 2). Significantly higher germination (93.00 %) was recorded by the GA_3 followed by KH_2PO_4 (88.33 %) and

Table 2: Effect of pre-sowing treatments on seed quality parameters

Treatment	Germination (%)	Root length (cm)	Shoot length (cm)	Seedling length (cm)	Seedling fresh weight (mg)	Seedling dry weight (mg)	Vigour index –I	Vigour index –II
Variety								
V_1	86.27	4.07	3.75	7.82	152.13	11.88	681.78	1039.03
V_2	83.93	3.69	3.26	6.95	134.33	10.39	589.03	883.94
S.Em ±	0.45	0.02	0.02	0.02	0.62	0.05	3.54	6.56
CD at 5 %	1.32	0.06	0.05	0.07	1.82	0.15	10.44	19.40
Treatment								
P_1	80.17	2.60	2.58	5.17	94.30	7.86	414.87	630.42
P_2	83.00	3.72	3.47	7.19	117.52	9.79	597.25	813.35
P_3	93.00	4.68	3.77	8.45	189.97	13.83	786.27	1287.08
P_4	81.00	3.29	3.04	6.34	104.08	8.67	513.58	703.20
P_5	88.33	5.12	4.67	9.79	210.30	15.53	865.08	1373.37
S.Em ±	0.71	0.03	0.03	0.04	0.97	0.08	5.59	10.40
CD at 5 %	2.09	0.09	0.08	0.10	2.87	0.24	16.50	30.67
Interaction								
V_1P_1	81.00	2.75	2.72	5.46	99.93	8.33	442.43	674.65
V_1P_2	84.00	3.99	3.72	7.72	124.63	10.39	648.53	872.17
V_1P_3	94.33	4.85	4.06	8.92	198.90	14.57	841.07	1374.62
V_1P_4	82.33	3.46	3.21	6.67	109.33	9.11	549.15	750.11
V_1P_5	89.67	5.31	5.04	10.35	227.87	16.99	927.75	1523.59
V_2P_1	79.34	2.45	2.44	4.88	88.67	7.39	387.32	586.19
V_2P_2	82.00	3.44	3.22	6.66	110.40	9.20	545.96	754.53
V_2P_3	91.64	4.50	3.48	7.98	181.03	13.09	731.46	1199.55
V_2P_4	79.72	3.13	2.87	6.00	98.83	8.24	478.01	656.28
V_2P_5	87.00	4.92	4.30	9.22	192.73	14.06	802.41	1223.16
GM	85.10	3.88	3.51	7.39	143.23	11.14	635.41	961.49
S.Em ±	1.00	0.04	0.04	0.05	1.38	0.12	7.71	14.70
CD at 5 %	NS	NS	0.11	0.15	4.06	0.34	23.33	43.37
CV (%)	2.04	1.98	1.88	1.16	1.66	1.79	2.16	2.65

Variety: V_1: Gujarat Cumin 2 and V_2: Gujarat Cumin 4

Treatments: P_1: Control, P_2: IAA (Indole Acetic Acid, 100 ppm), P_3: GA_3 (Gibberellic Acid, 200 ppm), P_4: Cytokinin (100 ppm), P_5: KH_2PO_4 (3 %)

significantly lower by non-primed seeds (80.17 %). GC 2 primed with GA_3 recorded highest germination (94.33 %) followed by the GC 4 primed with GA_3 (91.64 %) and non-primed seeds of variety GC 4 recorded lowest (79.34%). The best result was found in GA_3, a growth promoting hormone, which stimulated cell enlargement, RNA and DNA synthesis, repair of RNA and protein synthesis, and increased seed reserve depletion, seed reserve utilization efficiency, and emergence percentage. The priming treatment KH_2PO_4 was effective in improving germination percentage, due to increased usage of nutrient reserve and α-amylase activity. Hoseini *et al.* (2013), Heidari and Sadeghi (2014), Amirnia and Ghiyasi (2016), Piri *et al.* (2018), Jayamani *et al.* (2020) and Vidyarthi (2022) supported those finding.

The GC 2 and GC 4 recorded significantly higher (4.07 cm) and lower (3.69 cm) root length, respectively. Significantly highest root length was recorded by KH_2PO_4 (5.12 cm), followed by GA_3 (4.68 cm) and significantly lowest by unprimed seeds (2.60 cm).GC 2 primed with KH_2PO_4 recorded highest root length (5.31 cm) followed by GC 4 primed with KH_2PO_4 (4.92 cm) and lowest by non-primed seeds of GC 4 (2.45 cm). Seed priming can activate the metabolic processes within the seed to trigger early emergence of the radicle. The superiority in root length of GC 2 variety compared to GC 4 is due to their genetic makeup, physiological nature and response to priming treatments. KH_2PO_4 priming was associated with more potassium and phosphorous accumulation in seeds, which induced resistance. The results are in accordance with thoses of Nawaz *et al.* (2013), Jayamani *et al.* (2020) and Vidyarthi (2022).

The GC 2 and GC 4 recorded higher (3.75 cm) and lower (3.26 cm) shoot length, respectively. The highest shoot length (4.67 cm) was recorded by KH_2PO_4 followed by GA_3 (3.77 cm) and lowest by unprimed seeds (2.58 cm). GC 2 primed with KH_2PO_4 recorded significantly highest shoot length (5.04 cm), followed by GC 4 primed with KH_2PO_4(4.30 cm) and lowest (2.44 cm) by unprimed seeds of GC 4. These results are similar to those of Nawaz *et al.* (2013), Jayamani *et al.* (2020) and Vidyarthi (2022).

There was highest seedling length (9.79 cm) recorded by KH_2PO_4 followed by GA_3 (8.45 cm) and lowest (5.17 cm) by non-primed seeds. GC 2 primed with KH_2PO_4 recorded significantly highest seedling length (10.35 cm) followed by the GC 4 primed with KH_2PO_4(9.22 cm) and significantly lowest by non-primed seeds GC 4 (4.48 cm). Seed priming with osmotic solution can improve germination and shoot and root length through metabolic activation. This is due to increased RNA and protein synthesis, more availability of ATP and faster embryo growth. KH_2PO_4priming has also been shown to activate seed germination through ATPase activation, acid phosphatase and RNA synthase. These research findings are similar with Hoseini *et al.* (2013), Nawaz *et al.* (2013), Heidari and Sadeghi (2014), Piri *et al.* (2018) and Vidyarthi (2022).

The GC 2 and GC 4 recorded significantly higher (152.13 mg) and lower (134.33 mg) seedling fresh weight, respectively. Significantly highest seedling fresh weight recorded by KH_2PO_4 (210.30 mg) followed by GA_3 (189.97 mg) and significantly lowest in unprimed seeds (94.30 mg). GC 2 primed with KH_2PO_4 recorded significantly highest seedling fresh weight (227.87 mg) followed by GC 2 primed with GA_3 (198.90 mg) and significantly lowest in non-primed seeds of GC 4 (88.67 mg). Seed priming with KH_2PO_4 increased nutrient supply to the developing seedling, leading to higher seedling fresh weight. Phosphorous improved early growth and resulted in higher seedling growth, leading to healthy seedlings with more seedling fresh weight. These results are in accordance with those of Hoseini *et al.* (2013), Heidari and Sadeghi (2014), Erman *et al.* (2021).

The GC 2 and GC 4 recorded higher (11.88 mg) and lower (10.39 mg) seedling dry weight, respectively. Significantly highest seedling dry weight was recorded in KH_2PO_4 (15.53 mg) followed by GA_3 (13.83 mg) and significantly lowest in unprimed seeds (7.86 mg). GC 2 primed with KH_2PO_4 recorded significantly highest seedling dry weight (16.99 mg) followed by GC 2 primed with GA_3 (14.57 mg) and significantly lowest in non-primed seeds of GC 4 (7.39 mg). The seedling dry weight is the consequence of plant physiological and biological activity. KH_2PO_4 has been shown to activate seed germination through ATPase activation, acid phosphatase and RNA synthase, resulting in higher seedling dry weight. The findings are in coincidence with those of Hoseini *et al.* (2013), Danesh-Talab *et al.* (2014), Heidari and Sadeghi (2014) and Jayamani *et al.* (2020).

The GC 2 and GC 4 recorded significantly higher (681.78) and lower (589.03) seedling vigour index-I, respectively. The highest seedling vigour index-I was recorded by the KH_2PO_4 (865.08), followed by GA_3 (786.27) and significantly lowest by control (414.87). GC 2 primed with KH_2PO_4 recorded significantly highest seedling vigour index-I (927.75) followed by GC 2 primed with GA_3 (841.07) and significantly lowest by unprimed (control) seeds of variety GC 4 (387.32). Seed priming with treatments such as KH_2PO_4, GA3 and other growth hormones increased seedling vigour index, partially mitigating the harmful effect of stress and other outer parameters. KH_2PO_4 increased seedling growth by attributing to increased nutrient content in embryo and stimulating the synthesis of hydrolytic enzymes. Similarally, GC 2 and GC 4 recorded significantly higher (1039.03) and lower (883.94) seedling vigour index-II, respectively.

The significantly highest seedling vigour index-II (1373.37) was recorded by KH_2PO_4 followed by GA_3 (1287.08) and significantly lowest by control (630.42). GC 2 primed with KH_2PO_4 recorded significantly highest seedling vigour index-II (1523.59),followed by GA_3 primed with GC 2 (1374.62) and significantly lowest by unprimed seeds of GC 4. Primed seeds produce vigorous seedlings with increased seedling dry weight of cumin varieties. Similar results were reported by Heidari and Sadeghi (2014), Amirnia and Ghiyasi (2016), Jayamani *et al.* (2020) and Lunagariya *et al.* (2024).

CONCLUSION

Priming with GA_3 and KH_2PO_4 improved seed yield and quality parameters in field and laboratory condition respectively. The priming treatments were effective for better and uniform growth, high yield, rapid germination and high seedling vigour.

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Current Horticulture 14(3): 56-59, July–September 2026
DOI: 10.5958/2455-7560.2026.00039.7
Received: July 28, 2026; Revised: 4 September 2026: Accepted: 4 September 2026

Research Article

Harnessing multifunctional *Bacillus* sp. as bioinoculant for sustainable brinjal (*Solanum melongena*) production

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ABSTRACT

The study evaluated the effect of an indigenous *Bacillus* sp. NITR-3, isolated from the aerobic rice ecosystem of ICAR-IARI, New Delhi and was initially characterized for nitrous oxide reducing capacity and later on explored with multiple plant growth promoting traits, on growth, yield, fruit quality and rhizosphere biological properties of two contrasting brinjal (*Solanum melongena*) varieties, Pusa Uttam and Pusa Shyamla, under pot conditions. The plants received recommended dose of fertilizers (RDF) supplemented with *Bacillus* sp. (NITR-3) inoculation significantly increased individual fruit weight and total fruit number in both varieties compared with RDF alone. Fruit quality response was variety dependent, with Pusa Shyamla exhibiting significantly higher total phenolic contents following bacterial inoculation, whereas these parameters remained statistically unchanged in Pusa Uttam. The simultaneous improvement in crop productivity, antioxidant quality and soil biological health demonstrates the multifunctional nature of the bacterial isolate. Given its previously established nutrient solubilizing ability, phytohormone production, siderophore production and nitrous oxide reduction capacity, *Bacillus* sp. NITR-3 represents a promising bioinoculant for improving yield in brinjal. The study highlights the importance of variety specific responses to PGPR and supports the use of indigenous beneficial microorganisms to enhance vegetable productivity while promoting sustainable soil health.

Key words: *Bacillus* sp.; Brinjal; PGPR; Phenolics; Phosphate solubilizing bacteria; Potassium solubilizing bacteria; Soil health

Brinjal (*Solanum melongena* L.) is one of the most important Solanaceous vegetable crops cultivated throughout tropical and subtropical regions. Due to its wide adaptive nature, year-round cultivation and high economic value, it plays an important role in food and nutritional security (Tomar and Saha, 2018). Brinjal fruits are rich in dietary fibre, vitamins, minerals, phenolic compounds, flavonoids, anthocyanins and other antioxidant that contribute to human health (Daunay and Hazra, 2012; Nandi *et al.,* 2021; Lyngdoh *et al.,* 2025).

Continuous dependence on mineral fertilizers has increased crop productivity but also declined nutrient use efficiency, nutrient imbalance, reduced soil biological activity and environmental concerns associated with nutrient losses (Ladha *et al.,* 2022). Consequently, integrating beneficial microorganisms with recommended dose of fertilizers (RDF) has emerged as an effective strategy for improving crop productivity while maintaining soil health.

Among plant growth-promoting rhizobacteria (PGPR), *Bacillus* spp. are considered as one of the most promising microbial inoculants due to their ability to form stress-resistant endospores and survive under diverse environmental conditions. These bacteria promote plant growth through multiple mechanisms, including phosphate and potassium solubilization, phytohormone production, siderophore secretion, biological nitrogen fixation, biofilm formation and suppression of phytopathogens, thereby enhancing nutrient acquisition, plant growth and stress tolerance (Backer *et al.,* 2018; Aloo *et al.,* 2019). Integration of *Bacillus*-based bioinoculants with mineral fertilizers has also been reported to improve fertilizer use efficiency, soil microbial activity, and crop productivity (Adesemoye *et al.,* 2009). Therefore, study evaluated an innovative multifunctional *Bacillus* sp. based bioinoculant technology integrated with RDF for improving the growth, yield, fruit quality and soil health of two contrasting brinjal varieties under pot conditions.

MATERIALS AND METHODS

A pot experiment was conducted during the Kharif season of 2021 at ICAR–Indian Agricultural Research Institute (IARI), New Delhi, India (28°38′ N, 77°10′ E; 228 m amsl). The experimental soil (0-15 cm) was sandy loam with pH 7.3, EC 0.28 dS m^{-1}, organic carbon 0.48%, available N 235 kg ha^{-1}, available P 18.6 kg ha^{-1}, and available K 265 kg ha^{-1}. Soil analyses were performed following standard methods (Jackson, 1973; Subbiah and Asija, 1956).

The experiment was laid out in a completely randomized design (CRD) with two brinjal varieties, Pusa Uttam (purple round fruited) and Pusa Shyamla (purple long fruited), (Figure 1) two treatments and three replications. Plastic pots (30 cm diameter) containing

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10 kg of soil were used. Treatments comprised T_1: Recommended dose of fertilizers (RDF) and T_2: RDF + *Bacillus* sp. NITR-3. Nitrogen was applied in split doses, while phosphorus and potassium were applied at basal through urea, single superphosphate and muriate of potash, respectively.

The plant growth-promoting isolate NITR-3 was obtained from the rhizosphere of aerobic rice at ICAR-IARI and identified as *Bacillus* sp. by 16S rRNA gene sequencing (27F/1492R primers) followed by BLAST analysis against the NCBI GenBank database). The inoculum was prepared in nutrient broth to approximately 10^8 CFU mL^{-1} ($OD_{600} \approx 0.8–1.0$). Seedlings were root-dip inoculated for 30 min before transplanting, followed by application of 100 mL bacterial suspension as a soil drench around the root zone. Control plants received sterile distilled water.

Bacillus sp. NITR-3 was evaluated for IAA production, phosphate, potassium and zinc solubilization, siderophore production, ammonia production, HCN production, ACC deaminase activity and nitrous oxide (N_2O) reduction potential using standard microbiological protocols (Pikovskaya, 1948; Schwyn and Neilands, 1987; Penrose and Glick, 2003).

Standard crop management practices were followed throughout the experiment. Growth parameters (plant height, plant spread, leaf length and primary branches), yield attributes (fruit length, diameter, fruit index, fruits $plant^{-1}$, single fruit weight, yield $plant^{-1}$ and yield ha^{-1}), fruit quality traits (total phenolics and anthocyanins), and post-harvest rhizosphere biological properties [phosphate-solubilizing bacteria (PSB) and potassium-solubilizing bacteria (KSB)] were determined using standard procedures.

Completely Randomized Design (CRD) was followed and the experimental data were analyzed for variance (ANOVA). Treatment means were compared using the least significant difference (LSD) test at the 5% probability level. Statistical analyses were performed using R.

RESULTS AND DISCUSSION

Application of *Bacillus* sp. NITR-3 in combination with the recommended dose of fertilizers (RDF) positively influenced vegetative growth, fruit characteristics and yield of both brinjal varieties (Tables 1 and 2). Pusa Uttam exhibited greater vegetative growth than Pusa Shyamla, recording higher plant height, plant spread and larger leaves under both treatments. Bacillus inoculation significantly increased plant spread and the number of primary branches in both varieties, whereas improvements in plant height and leaf length were not significant. Fruit characteristics also improved following microbial inoculation.

In Pusa Uttam, single fruit weight increased from 173.67 to 186.33 g, fruit length from 10.67 to 13.67 cm, and fruit diameter from 8.33 to 11.00 cm. Similarly, in Pusa Shyamla, single fruit weight increased from 90.67 to 98.33 g, fruit length from 17.67 to 20.00 cm and fruit diameter from 4.67 to 6.67 cm. Fruit index remained statistically unchanged, although a slight reduction in Pusa Shyamla indicated proportionally greater fruit thickening after inoculation. *Bacillus* application also significantly enhanced reproductive performance, increasing the number of fruits per plant from 9.33 to 11.33 in Pusa Uttam and from 16.00 to 23.00 in Pusa Shyamla, resulting in corresponding increases in yield per plant from 1.49 to 1.68 kg and 1.80 to 2.07 kg, respectively.

Consequently, marketable fruit yield increased significantly in both varieties, from 31.22 to 35.35 t ha^{-1} (13.23%) in Pusa Uttam and from 37.80 to 43.40 t ha^{-1} (14.81%) in Pusa Shyamla. Among all treatments, Pusa Shyamla inoculated with *Bacillus* sp. + RDF recorded the highest yield (43.40 t ha^{-1}). Although Pusa Shyamla was superior in overall productivity, Pusa Uttam maintained its characteristic larger, round fruits, indicating that both cultivars responded positively to Bacillus inoculation while retaining their distinct market preferred fruit types (Fig. 1).

Comprehensive radar plot illustrating the comparative performance of the two contrasting brinjal varieties under RDF alone (T_1) and RDF + Bacillus sp. NITR-3 (T_2) across multiple vegetative and yield-related traits (Fig. 2). In both varieties, inoculation with Bacillus sp. NITR-3 expanded the radar profile, indicating an

Table 1: Effect of *Bacillus* sp. NITR-3 inoculation on vegetative growth parameters of two brinjal varieties. [Values are presented as mean ± standard error of the mean (SeM) based on three replications].

Variety	Treatment	Plant height (cm)	Plant spread (cm)	Leaf length (cm)	Primary branches ($plant^{-1}$)
Pusa Uttam	RDF (T_1)	93.67 ± 2.75	142.33 ± 3.75	13.33 ± 0.76	7.33 ± 0.29
Pusa Uttam	RDF + *Bacillus* (T_2)	96.67 ± 3.82*ns*	148.33 ± 5.20*	14.00 ± 0.50*ns*	9.33 ± 0.29*
Pusa Shyamla	RDF (T_1)	63.00 ± 4.09	89.00 ± 1.80	13.67 ± 0.29	9.67 ± 0.76
Pusa Shyamla	RDF + *Bacillus* (T_2)	65.67 ± 2.57*ns*	93.33 ± 3.82*	14.33 ± 0.29*ns*	12.33 ± 0.29*
LSD(P≤0.05)		12.71	1.88	1.8	1.72
CV (%)		8.46	6.5	7.23	9.4

Table 2: Effect of *Bacillus* inoculation on growth, yield attributes and fruit yield of two brinjal varieties. [Values are presented as mean ± standard error of the mean (SeM) based on three replications].

Variety	Treatment	Fruit length (cm)	Fruit diameter (cm)	Fruit index	Fruits plant^{-1}	Single fruit weight (g)	Yield plant^{-1} (kg)	Yield (t ha^{-1})
Pusa Uttam	RDF (T_1)	10.67 ± 0.58	8.33 ± 0.29	1.29 ± 0.10	9.33 ± 0.58	173.67 ± 4.04	1.49 ± 0.04	31.22 ± 0.85
Pusa Uttam	RDF + *Bacillus* (T_2)	13.67 ± 0.58*	11.00 ± 0.87*	1.26 ± 0.09*ns*	11.33 ± 0.76*	186.33 ± 4.65*	1.68 ± 0.04*	35.35 ± 0.80*
Pusa Shyamla	RDF (T_1)	17.67 ± 1.26	4.67 ± 0.29	3.87 ± 0.51ns	16.00 ± 0.50	90.67 ± 2.02	1.80 ± 0.05	37.80 ± 1.05
Pusa Shyamla	RDF + *Bacillus* (T_2)	20.00 ± 1.00*	6.67 ± 0.29*	3.03 ± 0.28*ns*	23.00 ± 1.50*	98.33 ± 1.76*	2.07 ± 0.03*	43.40 ± 0.61*
LSD($P \leq 0.05$)		3.39	1.88	1.13	3.48	12.64	0.151	3.17
CV (%)		11.63	13.04	25.48	12.39	4.9	4.56	4.56

overall improvement in plant growth and productivity compared with RDF alone. The enhancement was particularly evident for plant height, plant spread, number of primary branches, average fruit weight, fruit length, number of fruits per plant, yield per plant and yield per hectare. Pusa Uttam exhibited superior plant stature and larger fruit size, whereas Pusa Shyamla produced a greater number of fruits and higher overall yield. The radar plot further demonstrates that Bacillus sp. NITR-3 positively influenced multiple agronomic traits simultaneously without adversely affecting variety specific fruit characteristics, highlighting its potential as an effective plant growth promoting inoculant for sustainable brinjal production.

Fig. 1: Fruits harvested from *Bacillus* sp. applied along with RDF for both the variety

The total phenolic content of brinjal fruits was significantly influenced by both cultivar and *Bacillus* sp. NITR-3 inoculation (Fig. 3). Pusa Shyamla consistently recorded higher phenolic content than Pusa Uttam, indicating inherent genotypic differences in antioxidant metabolite accumulation. In Pusa Uttam, total phenolic content remained statistically at par between RDF (T_1) and RDF + *Bacillus* (T_2) ($P > 0.05$), whereas Pusa Shyamla exhibited a significant increase from 2.38 to 2.70 mg GAE g^{-1} fresh weight following bacterial inoculation ($P \leq 0.05$). The enhanced phenolic accumulation in Pusa Shyamla may be attributed to improved nutrient acquisition and phytohormone mediated activation of the phenylpropanoid pathway, resulting in greater synthesis of antioxidant compounds (Bhattacharyya and Jha, 2012; Backer *et al.*, 2018). The absence of a significant response in Pusa Uttam suggests that PGPR-mediated regulation of secondary metabolism is genotype dependent. Importantly, the increased phenolic content in Pusa Shyamla was accompanied by higher fruit yield, indicating that *Bacillus* sp. NITR-3 simultaneously improved both productivity and nutritional quality without compromising crop performance.

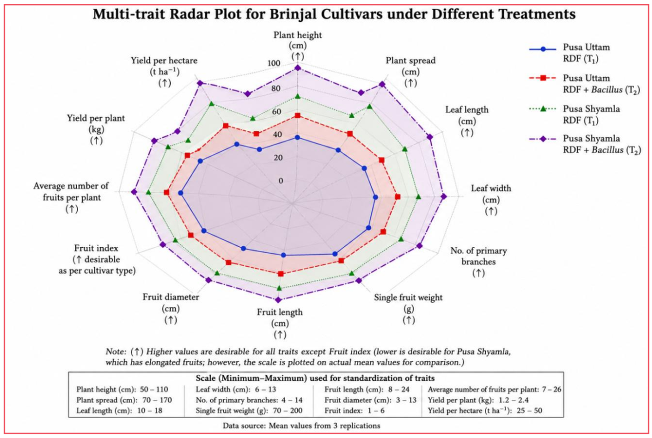

Fig. 2: Integrated visualization of growth responses of brinjal varieties to *Bacillus* based biofertilizer using a multi-trait radar plot.

Inoculation with *Bacillus* sp. integrated with the recommended dose of fertilizers (RDF) significantly improved vegetative growth, fruit characteristics and yield of both brinjal varieties. The enhanced plant growth is attributed to the multifunctional plant growth promoting traits of *Bacillus*, including phytohormone production, nutrient solubilization and improved nutrient uptake, which collectively stimulate root development and biomass accumulation (Glick, 2012).

Bacillus inoculation also increased fruit length, diameter, single fruit weight and fruit yield, indicating improved assimilate partitioning and reproductive efficiency. Enhanced phosphorus and potassium availability together with microbial growth regulators likely promoted fruit development and sink strength (Bhattacharyya and Jha, 2012). While Pusa Uttam produced larger fruits, Pusa Shyamla exhibited greater increases in fruit number and overall productivity, suggesting genotype-dependent responses to microbial inoculation (Lucy *et al.*, 2004).

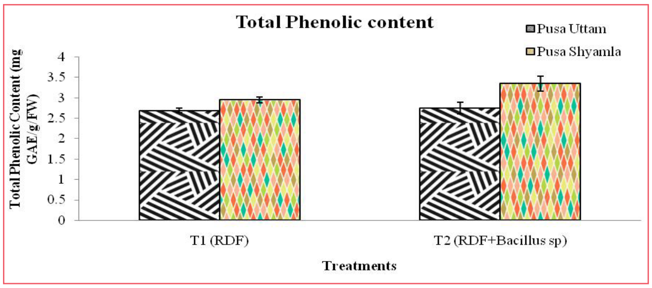

Fig. 3: Influence of *Bacillus* sp. NITR-3 on total phenolic content of fruits in contrasting brinjal varieties.

The significant yield improvement observed under RDF + *Bacillus* resulted from the combined increase in fruit number and fruit weight, reflecting enhanced nutrient use efficiency and rhizosphere functioning. These findings agree with previous reports demonstrating that *Bacillus*-based bioinoculants improve crop productivity by enhancing nutrient acquisition and overall plant performance (Backer *et al.,* 2018). Overall, integration of multifunctional *Bacillus* sp. with RDF represents a promising and sustainable nutrient management strategy for improving brinjal productivity while reducing dependence on chemical fertilizers.

CONCLUSION

The study demonstrated that *Bacillus* sp. NITR-3, when integrated with recommended dose of fertilizers, significantly enhanced brinjal growth, yield, fruit quality, and rhizosphere biological activity under pot conditions. Bacillus inoculation increased fruit number, single fruit weight, and marketable yield in both Pusa Uttam and Pusa Shyamla, while significantly enhancing total phenolic content only in Pusa Shyamla, indicating genotype-dependent improvement in antioxidant quality. The inoculated treatments also recorded higher populations of phosphate- and potassium-solubilizing bacteria, reflecting improved rhizosphere functioning and nutrient cycling.

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Current Horticulture 14(3): 60-63, July–September 2026
DOI: 10.5958/2455-7560.2026.00040.3
Received: July 19, 2025; Revised: 1 July, 2026: Accepted: 4 September 2026

Research Article

Effect of foliar micronutrient application on yield, quality and return of garlic (*Allium sativum*) in Western Rajasthan

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Abstract

A field experiment was conducted at the Dr B.R. Choudhary Agricultural Research Station, Mandor (Jodhpur) to evaluate the effect of foliar application of micronutrients on growth, yield and return of garlic (*Allium sativum* L.) during *rabi* seasons of 2022–23 and 2023–24. The randomized block design with three replications and eight micronutrient treatments was used. Foliar sprays of different micronutrient concentrations were applied 30, 60 and 90 days after planting. The results revealed that treatment T_8 ($ZnSO_4$ 0.5% + $FeSO_4$ 0.5% + Boron 0.25%) significantly improved plant height (50.97 cm), number of leaves/plant (10.13) and neck thickness (10.07 mm). Yield parameters, including polar diameter of bulb (36.68 mm), equatorial diameter of bulb (41.75 mm), fresh weight of bulb (34.39 g), number of cloves/ bulb (23.21), total soluble solids (39.70 °Brix) and bulb yield (57.60 q/ha), were also highest under treatment T_8. This treatment recorded the maximum net return (₹3,84,222/ha) and most favourable benefit: cost ratio (5.71), indicating its economic superiority over other treatments.

Key words: Boron, Zinc, Yield, Quality, Parameters, Economics, Micronutrients

Garlic (*Allium sativum* L.), a member of family *Amaryllidaceae*, is considered the second most important bulbous vegetable crop after onion. India ranks second globally in garlic production after China. Major garlic-producing states include Madhya Pradesh, Rajasthan, Gujarat, Uttar Pradesh and Punjab. However, average productivity of garlic in India is still lower than the crop's genetic yield potential indicating a substantial yield gap. This yield gap is largely attributed to suboptimal management practices, continuous use of traditional low-yielding varieties, insufficient fertilizer use and depletion of both macro- and micronutrients from the soil (Singh *et al.,* 2014 and Rathore *et al.,* 2017). Essential micronutrients like zinc (Zn), copper (Cu), iron (Fe) and boron (B) are involved in vital physiological processes such as respiration, cell division, chlorophyll formation, enzyme activation, photosynthesis, nitrogen metabolism and reproductive development (Tiwari *et al.,* 2010). Deficiency of these micronutrients leads to poor vegetative growth, reduced photosynthetic efficiency, impaired bulb development and ultimately low yields in garlic (Rathore *et al.,* 2017).

Foliar application ensures rapid nutrient absorption through leaf surfaces, bypassing soil-related constraints and supplying nutrients directly during critical growth stages (Vekaria *et al.,* 2018). The foliar application of micronutrients can significantly enhance plant growth, improve physiological activity and boost both yield and quality parameters in bulb crops like garlic and onion (Singh *et al.,* 2014). Moreover, it promotes efficient nutrient use and minimizes environmental losses compared to conventional fertilization methods. Given the nutritional and economic importance of garlic and the role of micronutrient management in enhancing productivity, the present investigation was undertaken to assess the effect of foliar application of different micronutrient combinations on growth, yield and return of garlic under the agroclimatic conditions of western Rajasthan.

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MATERIALS AND METHODS

A field experiment was conducted during *rabi* seasons (2022–23 and 2023–24) at the Dr B.R. Choudhary Agricultural Research Station, Mandor, Jodhpur (Rajasthan). The experimental site is located in semi-arid region with sandy loam soil characterized by low organic matter. Garlic cultivar Yamuna Safed-3 was selected for study. The experiment was laid out in a randomized block design comprising eight treatments with four replications. Each plot measured 2.4 m × 3.0 m with planting done at a spacing of 15 cm × 8 cm. The treatments consist of various concentrations of micronutrients (Zn, Fe and B) applied 30, 60 and 90 days after planting through foliar application. The treatments include: T_1: control (water spray), T_2: $ZnSO_4$ 0.5%, T_3: $FeSO_4$ 0.5%, T_4: Boron 0.25%, T_5: $ZnSO_4$ 0.5% + $FeSO_4$ 0.5%, T_6: $ZnSO_4$ 0.5% + boron 0.25%, T_7: $FeSO_4$ 0.5% + boron 0.25% and T_8: $ZnSO_4$ 0.5% + $FeSO_4$ 0.5% + boron 0.25%.

Ten plants were selected randomly from per plot as a unit for observations on plant height, number of leaves per plant and neck thickness at 60 and 90 DAP, polar diameter of bulb (mm), equatorial diameter of bulb (mm), fresh weight of bulb (g), number of cloves/bulb, TSS (°Brix) and bulb yield. Gross return, net return and B:C ratio were also calculated. Pooled data of the two years were used to analyzed as per Panse and Sukhatme (1984). Statistical analysis was performed using the OPSTAT statistical software developed by Sheoran (Sheoran *et al.,* 1998) and treatment means were compared using the critical difference (CD) test at the 5% level of significance.

RESULTS AND DISCUSSION

Among the treatments, T_8 ($ZnSO_4$ 0.5% + $FeSO_4$ 0.5% + boron 0.25%) consistently recorded superior performance across all parameters. The maximum plant height was observed in T_8 with 37.21 cm 60 days after planting (DAP) and 50.97 cm at 90 DAP, followed by T_6 (36.04 cm and 49.42 cm) and T_5 (35.77 cm and 48.85 cm), while the control treatment T_1 exhibited minimum plant height (33.13 and 45.54 cm). The enhanced plant height under micronutrient application may be attributed to synergistic effects of zinc, iron and boron which collectively promote cell elongation, meristematic activity and chlorophyll synthesis that ultimately supporting better vegetative growth (Marschner, 2012). Similar enhancements in garlic and onion were reported by Alam *et al.* (2019) and Kaur *et al.* (2022).

In number of leaves/plant, T_8 produced highest number (7.53 at 60 DAP and 10.13 at 90 DAP), followed by T_6 and T_5, whereas the control recorded minimum number of leaves. This improvement could be linked to increased photosynthetic activity and enhanced nutrient assimilation due to balanced micronutrient availability (Tiwari *et al.,* 2010). These results align with those of Rahman *et al.* (2022) and Singh *et al.* (2015) in garlic and onion. As similar, neck thickness showed significant variation with T_8 producing the maximum neck girth (7.41 mm at 60 DAS and 10.07 mm at 90 DAS) followed by T_6 and T_5 while minimum neck thickness was noted in T_1.

The increased neck girth may be associated with boron's role in strengthening cell walls and iron's contribution to improved chlorophyll synthesis, facilitating better assimilate translocation and overall plant vigor (Alam *et al.,* 2019 & Biswas *et al.,* 2020). The results demonstrate that foliar application of $ZnSO_4$, $FeSO_4$ and boron not only enhances individual growth traits but also synergistically improves the overall vegetative development of garlic.

The T_8 ($ZnSO_4$ 0.5% + $FeSO_4$ 0.5% + boron 0.25%) consistently outperformed all other treatments across parameters. The highest polar diameter (36.68 mm) and equatorial diameter (41.75 mm) were recorded under T_8, followed by T_6 and T_5 while smallest bulb dimensions were observed in the control (T_1) (Table 1). The significant increase in bulb size with micronutrient application may be attributed to enhanced photosynthate translocation and cell expansion due to the synergistic effects of zinc, iron and boron as also reported by Goyal *et al.* (2017) and Aske *et al.* (2017). The fresh weight of bulbs found a similar trend with T_8 recording the maximum bulb weight (34.39 g) followed by T_6 (32.26 g) and T_5 (28.45 g) while T_1 recorded the lowest bulb weight (23.79 g). The superiority of T_8 in fresh bulb weight can be ascribed to zinc's role in enzyme activation, protein synthesis and auxin production, which directly promote cell division and enlargement contributing to bulb growth (Marschner, 2012), in line with the findings of El-Tohamy *et al.* (2009), Jat *et al.* (2023) and Pramanik and Tripathy (2017).

Similarly, significant differences were observed in the number of cloves per bulb with T_8 producing the maximum cloves (23.51), followed by T_6 and T_5 and the lowest number of cloves was found in T_1. The increase in clove number under combined micronutrient application reflects improved nutrient uptake and metabolic efficiency that favors differentiation and clove formation (Vekaria *et al.,* 2018 and Rahman *et al.,* 2022). Total soluble solids (TSS) content ranged from 37.38 °Brix in T_1 to a maximum of 39.70 °Brix in T_8. This improvement in TSS could be linked to enhanced carbohydrate synthesis and storage resulting from better photosynthetic activity under balanced micronutrient supply, as similarly noted by Aske *et al.* (2017) and Kaur *et al.* (2022) in onion. In terms of total bulb yield, highly significant differences were noted among treatments. T_8 recorded highest yield (57.60 q/ha), followed by T_6 (54.21 q/ha) and T_5 (52.04 q/ha).

Among individual nutrient treatments, T_2 ($ZnSO_4$ 0.5%) performed best with a yield of 48.86 q/ha, indicating the standalone efficacy of zinc although inferior to the combined application. The minimum yield (41.26 q/ha) was recorded in the untreated control T_1. The significant enhancement in bulb yield under T_8 can be attributed to the collective roles of Zn, Fe and B in improving root activity, enzyme function, chlorophyll formation and assimilate partitioning towards bulb development (Marschner, 2012). Similar yield improvements with micronutrient application were also observed by Alam *et al.* (2019), Rahman *et al.* (2022), Singh *et al.* (2015) and Tyagi *et al.* (2025). The study establishes that combined foliar application of $ZnSO_4$ 0.5 %, $FeSO_4$ 0.5% and boron 0.25% concentration is most effective in maximizing bulb size, weight, number of clove, TSS content and overall bulb yield in garlic under semi-arid conditions.

Economic analysis

Economic evaluation revealed that T_8 provided the highest gross return (₹4,65,833/ha), net return

Table 1: Effect of foliar application of micronutrients on growth and yield attributes (pooled data of two years)

Treatment	Plant height (cm)	Plant height (cm)	No. of leaves/ plant	No. of leaves/ plant	Neck thickness (mm)	Neck thickness (mm)	Polar diameter of bulb (mm)	Equatorial diameter of bulb (mm)
	60DAP	90DAP	60DAP	90DAP	60DAP	90DAP		
T_1	33.13	45.54	6.56	7.76	6.34	8.31	30.16	33.80
T_2	35.45	47.50	6.83	8.36	6.93	8.80	32.02	36.77
T_3	34.59	46.40	6.70	8.00	6.77	8.60	30.81	35.74
T_4	34.94	47.09	6.76	8.19	6.80	8.73	31.15	36.35
T_5	35.77	48.85	7.00	9.26	7.12	9.53	34.15	38.26
T_6	36.04	49.42	7.13	9.41	7.09	9.75	34.13	39.72
T_7	35.56	48.34	6.89	8.65	6.87	9.17	34.16	37.45
T_8	37.21	50.97	7.53	10.13	7.41	10.07	36.68	41.75
SE(m)±	0.64	0.93	0.18	0.25	0.21	0.28	1.14	0.78
CD (5%)	1.84	2.66	0.50	0.72	0.61	0.81	3.26	2.24
CV (%)	3.65	3.88	5.06	5.76	6.15	6.20	6.95	4.19

Table 2: Effect of foliar application of micronutrients on yield, quality and economics (pooled data of two years)

Treatment	Fresh weight of bulb (g)	No. of clove/bulb	TSS (%)	Bulb yield (q/ha)	Gross return (₹/ ha)	Net return (₹/ ha)	B : C ratio
T_1	23.79	17.06	37.38	41.26	330192	254562	4.37
T_2	26.60	19.20	38.23	48.86	391527	311959	4.92
T_3	24.90	18.12	37.70	46.80	375776	296059	4.71
T_4	25.81	18.77	38.08	47.27	379709	300123	4.77
T_5	28.45	20.48	38.60	52.04	421530	340875	5.23
T_6	32.26	21.21	38.94	54.21	438963	358439	5.45
T_7	27.03	20.04	38.47	50.31	405527	324854	5.03
T_8	34.39	23.51	39.70	57.60	465833	384222	5.71
SE(m)±	1.59	0.77	0.32	2.37	21633	-	-
CD at 5%	4.55	2.18	0.92	6.75	61740	-	-
CV (%)	11.43	7.73	1.67	9.50	10.79	-	-

(₹3,84,222/ha) and B:C ratio (5.71), followed by T_6 and T_5 (Table 2). The control treatment recorded the lowest returns and B:C ratio. The results confirm the economic feasibility of combined foliar application of Zn, Fe and B. Similar economic benefits of micronutrient foliar feeding have been highlighted by Vekaria *et al.* (2018) and Biswas *et al.* (2020).

CONCLUSION

The foliar application of $ZnSO_4$ 0.5% + $FeSO_4$ 0.5% + boron 0.25% (T_8) consistently produced more plant growth, yield, bulb quality and economic returns in garlic. Therefore, T_8 can be recommended as the most effective treatment for maximizing both productivity and profitability. Alternatively, T_6 ($ZnSO_4$ 0.5% + boron 0.25%) also demonstrated promising results and may be adopted where simpler nutrient management is preferred.

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Current Horticulture 14(3): 64-69, July–September 2026
Research Article
DOI: 10.5958/2455-7560.2026.00041.5
Received: 7 March 2026; Revised: 15 June 2026: Accepted: 4 September 2026

Integrated nutrient management in strawberry (*Fragaria × ananassa*) under semi-arid region of Haryana

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Abstract

The study was carried out at the Crop Research Centre, Kaliwas Farm, SGT University, Gurugram (Haryana) to evaluate the influence of different combinations of inorganic fertilizers, Azotobacter, phosphate- solubilizing bacteria, and humic acid on growth, physiology, flowering, fruit quality, and yield of strawberry (*Fragaria × ananassa* Duch.) cv. Winter Dawn, during winter season of 2023–24. Eight treatment combinations, including control, RDF alone, and various biofertilizer and humic acid integrations, were evaluated under a randomized block design with three replications. The integrated nutrient treatments significantly enhanced plant height, number of leaves, leaf area, and plant spread. The chlorophyll content improved remarkably, indicating enhanced photosynthetic efficiency. The number of runners, days to first flowering, fruit setting percentage, and fruit/ plant, showed notable improvement with the application of biofertilizers and humic acid. Fruit physical characteristics (length, width weight, and volume) also improved progressively with enhanced nutrient combinations. The highest fruit yield per plant (575.50 g) and per hectare (12.11 t/ha) were obtained under T_8 (RDF 100% + Azotobacter + PSB + 2% humic acid), establishing it as the most effective INM treatment. The overall findings suggest that integrated nutrient management that combines chemical fertilizers with biological and organic sources enhances strawberry growth, productivity, and quality, and contributes to sustainable soil health.

Key words: Integrated nutrient management, Azotobacter, Humic acid, Growth, Yield, Winter Dawn

Strawberry (*Fragaria × ananassa* Duch.) belonging to family Rosaceae, 56 chromosomes (2n = 8x = 56) is rich in nutritional profile and health-promoting compounds (Singh *et al.*,2021).Its productivity is highly sensitive to climatic conditions, mineral nutrition, cultivar type, irrigation regime, and cultural practices (Nestby *et al.,* 2004). Due to its rapid growth and shallow root system, its crop requires continuous and balanced nutrient supply (Li *et al.,* 2010). Suboptimal nutrition not only limits yield but also compromises fruit texture, flavour, and shelf life. Therefore, nutrient management plays a central role in improving strawberry production efficiency and maintaining soil fertility. The Integrated Nutrient Management (INM), including the combined use of inorganic fertilizers, organic amendments, and microbial inoculants, has emerged as a promising strategy for sustainable strawberry cultivation. Biofertilizers, consisting of beneficial microorganisms, enhance soil nutrient availability and contribute to improved plant growth. Their use also reduces dependency on chemical fertilizers, lowers production costs, and minimizes environmental pollution (Beer *et al.,* 2017). Azotobacter colonizes rhizosphere of fruit crops and improves nitrogen availability, thereby enhancing metabolic processes and overall plant vigour (Verma and Rao, 2013). Similarly, phosphate solubilizing bacteria (PSB) play an essential role in converting the otherwise unavailable insoluble phosphate—constituting nearly 95–99% of total soil phosphorus—into plant-available forms through the secretion of organic acids and enzymes such as phytase (Gupta *et al.,* 1994). The humic acid enhances vegetative growth, nutrient mobility, and fruit yield, often showing synergistic effects when combined with biofertilizers (Martinez-Dela Crruz, 2022). The, combining chemical fertilizers with bioorganic sources improves nutrient availability while reducing nutrient losses, enhancing soil fertility, and sustaining long-term productivity (Macit *et al.,* 2007). Hence, an experiment was conducted to evaluate integrated nutrient management on strawberry in semi- arid Haryana.

MATERIALS AND METHODS

A field experiment was conducted at Kaliwas Farm of SGT University, Gurugram, Haryana, during winter season of 2023–24. The experimental field is geographically located at 28.48° N latitude and 76.89° E longitude, at an altitude of 217 meters above mean sea-level. The site falls under North-Western agroclimatic zone, characterized

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by a semi-arid climate, hot dry summers, and cool winters, with sandy loam soils predominating in the region. The experiment was laid out in a randomized block design along with Azotobacter, phosphate solubilizing bacteria, and 2% humic acid, either alone or in consortium. The details of treatments were: T_1: control, T_2: RDF 100% + *Azotobacter*, T_3: RDF 100% + PSB, T_4: RDF 100% + 2% humic acid, T_5: RDF 100% + *Azotobacter* + PSB, T_6: RDF 100% + PSB + 2% humic acid, T_7: RDF 100% + *Azotobacter* + 2% humic acid, T_8: RDF 100% + *Azotobacter* + PSB + 2% humic acid.

Strawberry Winter Dawn was used. Healthy runners were transplanted in raised beds at a spacing of 45 cm × 30 cm, maintaining optimum plant population. Routine cultural operations, irrigation, mulching, weeding, and plant protection measures were carried out uniformly. Treatments to ensure proper crop growth and minimize environmental variation. During randomly selected tagged plants within each plot. The recorded data were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for the randomized block design, and significance of treatment differences was tested at the 5 per cent level.

RESULTS AND DISCUSSION

Integrated nutrient management (INM) treatments enhanced plant height at all stages of growth (Table 1). At 30 DAP, maximum plant height (8.50 cm) was recorded under treatment T_8 (RDF 100% + Azotobacter + PSB + 2% humic acid), followed by T_7 (7.61 cm) and T_6 (6.72 cm). The minimum plant height (4.38 cm) was observed in the control (T_1). A similar trend was observed at 60 DAP, where T_8 again exhibited highest plant height (13.23 cm), followed by T_7 (12.17 cm), while lowest value (7.02 cm) continued to be recorded under T_1. At 90 DAP, treatment T_8 maintained its superiority with a plant height of 16.94 cm, followed by T_7 (15.55 cm) and T_6 (14.57 cm). The control (10.79 cm) recorded lowest growth. By 120 DAP, maximum plant height (22.15 cm) was again attained under T_8, with the next highest value noted in T_7 (21.46 cm). The minimum plant height (13.51 cm) remained in the control treatment. Similar improvements in vegetative growth under integrated nutrient management have been reported by Singh *et al.* (2017), Mor *et al.* (2022) and Das *et al.*(2017).

The number of leaves was positively influenced by the application of integrated nutrient management (INM) practices (Table 1). At 30 DAP, the highest leaf count (7.64) was recorded under T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed by T_7 (7.49), whereas the control (T_1) produced minimum (4.24). A similar trend continued at 60 DAP, where T_8 recorded the maximum number of leaves (13.47), while T_1 again showed the lowest value (7.56). At 90 DAP, leaf production increased across treatments, with T_7 (19.74) and T_8 (19.65) producing the highest counts, compared to the control (15.59). By 120 DAP, T_8 remained superior with 22.41 leaves, followed by T_7 (21.87), while T_1 recorded the lowest number (17.64). Similar findings on improved vegetative growth in strawberry under INM have been reported by Singh *et al.*(2017) Mor *et al.* (2024)and Das *et al.* (2017).

Plant spread in north–south direction increased consistently with the application of integrated nutrient management treatments (Table 1). At 30 DAP, maximum plant spread (15.59 cm) was recorded under T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed closely by T_7 (15.55 cm), whereas minimum spread (7.26 cm) was observed in the control (T_1). At 60 DAP, T_8 again produced the highest plant spread (20.49 cm), followed by T_7 (20.33 cm), while T_1 recorded the lowest (11.56 cm). A similar trend continued at 90 DAP, with T_8 (25.12 cm) and T_7 (25.01 cm) showing greater canopy expansion compared to other treatments. The control treatment exhibited the least spread (17.05 cm). By 120 DAP, the maximum spread (31.82 cm) was obtained under T_8, followed by T_7 (30.65 cm). The minimum spread (21.94 cm) remained under the control. The superior performance of T_8 may be attributed to synergistic effect of biofertilizers and humic acid, which enhance nutrient uptake, root activity, and vegetative growth. Sangwan *et al.* (2025) and Thumar *et al.* (2026).

The plant spread in east–west direction showed a notable improvement with the application of integrated nutrient management treatments (Table 1). At 30 DAP, maximum spread (14.69 cm) was observed in T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed by T_7 (14.25 cm) and T_6 (14.11 cm), while lowest spread (7.48 cm) was recorded under the control (T_1). At 60 DAP, T_8 continued to record the highest plant spread (18.87 cm), closely followed by T_7 (18.56 cm), whereas T_1 again showed the minimum (11.26 cm). A similar trend was observed at 90 DAP, where T_8 produced the greatest canopy spread (22.64 cm), followed by T_7 (22.41 cm). The control treatment remained the lowest (13.69 cm). By 120 DAP, T_8 maintained its superiority with the highest plant spread (32.12 cm), while T_7 (31.84 cm) also showed substantial improvement. The minimum spread (25.69 cm) continued to be recorded in T_1. The superior performance of T_8 can be attributed to the combined effects of *Azotobacter*, PSB, and humic acid, which together enhance nutrient availability, photosynthetic efficiency, and vegetative expansion. Similar improvements in canopy spread of strawberry under INM have been reported by Singh *et al.* (2017) and Das *et al.* (2017).

Table 1: Effect of INM practices on plant growth parameters, leaf area, and chlorophyll content of strawberry at different days after planting (DAP).

Treatment	Plant height (cm) DAP				Number of leaves (DAP)				Plant spread (cm) N-S DAP				Plant spread (cm) E-W DAP				Leaf area (cm^2) DAP				Chlorophyll contains (mg/g)		
	30	60	90	120	30	60	90	120	30	60	90	120	30	60	90	120	30	60	90	120	Chl A	Chl B	Chl.con.
T_1	4.38	7.02	10.79	13.51	4.24	7.56	15.59	17.64	7.26	11.56	17.05	21.94	7.48	11.26	13.69	25.69	19.56	29.53	37.58	40.21	1.05	0.30	2.18
T_2	5.32	8.22	11.88	14.91	5.57	10.64	17.08	19.37	8.58	14.03	19.36	23.54	9.63	13.65	16.87	27.54	21.54	31.52	39.36	46.51	1.08	0.41	2.35
T_3	4.97	7.93	11.6	14.46	5.02	9.58	16.98	18.47	8.01	13.51	18.52	22.62	8.47	12.47	15.45	26.45	20.14	30.48	38.58	44.25	1.06	0.36	2.36
T_4	5.71	9.55	12.85	16.21	6.54	11.48	17.47	19.87	10.36	15.05	21.36	25.48	12.64	15.96	20.96	28.85	22.41	32.43	40.47	48.84	1.09	0.45	2.55
T_5	6.49	10.5	13.69	17.98	6.85	12.36	18.65	20.65	11.68	18.87	23.46	26.58	13.96	16.58	20.84	30.68	23.68	33.45	42.69	51.52	1.11	0.51	2.75
T_6	6.72	11.2	14.57	18.97	7.12	11.47	18.84	20.84	12.79	19.94	24.67	28.64	14.11	17.87	21.47	28.78	24.72	35.46	44.41	52.08	1.13	0.56	2.85
T_7	7.61	12.17	15.55	21.46	7.49	12.42	19.74	21.87	15.55	20.33	25.01	30.65	14.25	18.56	22.41	31.84	25.85	36.21	45.03	52.32	1.16	0.58	2.95
T_8	8.5	13.23	16.94	22.15	7.64	13.47	19.65	22.41	15.59	20.49	25.12	31.82	14.69	18.87	22.64	32.12	26.64	36.58	45.22	52.69	1.18	0.62	3.56
C.D.	4.38	7.02	10.79	13.51	0.37	1.06	0.77	1.04	0.40	0.26	0.36	1.82	0.48	0.48	0.55	1.02	1.90	4.00	0.98	0.007	N/A	0.07	0.26

Table 2: Effect of different INM treatments on runner production, flowering, harvesting, fruit yield attributes, and yield of strawberry.

Treatment	No. of runner/ plant	Days of first flowering	Days of first harvesting	No. of fruits/ plant	Fruit set (%)	Fruit length (cm)	Fruit width (cm)	Fruit wt. (g)	Fruit vol. (ml)	Fruit yield (g/plant)	Fruit yield (tonnes/ha)
T_1	2.51	47.54	85.62	13.56	67.81	2.92	2.64	11.54	16.84	556.48	9.22
T_2	2.35	49.84	87.53	12.84	67.26	2.88	2.56	11.36	16.59	545.86	8.65
T_3	3.48	44.84	82.13	14.13	69.55	3.35	3.12	13.67	17.46	533.15	9.13
T_4	3.41	42.87	79.35	15.57	71.48	3.52	3.37	14.51	18.22	538.92	10.01
T_5	3.78	44.32	75.48	16.64	73.36	3.74	3.46	15.34	18.87	545.08	10.71
T_6	4.24	43.89	72.82	17.41	75.45	3.91	3.51	16.57	19.55	567.48	11.58
T_7	5.75	42.78	70.24	18.05	85.00	4.39	4.13	17.46	20.43	575.50	12.11
T_8	1.72	0.56	0.13	0.005	0.63	0.59	0.37	0.70	0.73	10.84	1.78
C.D.	2.35	58.54	89.21	12.51	65.87	2.64	2.15	10.15	15.47	526.97	8.17

T_1-Control; T_2-RDF 100%+ Azotobacter; T_3-RDF 100% +PSB; T_4-RDF 100% +2% HA; T_5-RDF 100%+ AZ+PSB; T_6-RDF 100% +PSB+2% HA; T_7-RDF 100%+ AZ +2% HA; T_8-RDF 100%+ AZ +2% HA+PSB

Leaf area increased steadily under different integrated nutrient management (INM) treatments (Table 1). At 30 DAP, the largest leaf area (26.64 cm^2) was observed in T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed by T_7 (25.85 cm^2), while the control recorded the minimum (19.56 cm^2). A similar trend continued at 60 DAP, where T_8 and T_7 reported the highest leaf areas (36.58 cm^2 and 36.21 cm^2, respectively), compared with the control (29.53 cm^2). At 90 DAP, leaf expansion was highest under T_8 (45.22 cm^2), followed closely by T_7 (45.03 cm^2), whereas lowest value (37.58 cm^2) remained in the control. By 120 DAP, T_8 maintained its superiority (52.69 cm^2), with T_7 (52.32 cm^2) and T_6 (52.08 cm^2) also showing notable improvements. The control had the smallest leaf area (40.21 cm^2). Similar observations of increased leaf area due to biofertilizers and humic substances in strawberry and other horticultural crops have been reported by Rana *et al.* (2015), Khalid *et al.* (2017), Mor *et al.* (2025), Kumar and Singh, (2020).

The chlorophyll content of leaves increased progressively with the application of integrated nutrient management treatments (Table 1). For chlorophyll a, the highest value (1.18 mg/g) was observed in T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed by T_7 (1.16 mg/g) and T_6 (1.13 mg/g). The lowest chlorophyll a content (1.05 mg/g) occurred in the control (T_1). A similar pattern was recorded for chlorophyll b, where T_8 exhibited the maximum value (0.62 mg/g), followed by T_7 (0.58 mg/g). The minimum value (0.30 mg/g) remained in the control treatment. Total chlorophyll content also followed the same trend, with T_8 recording the highest (3.56 mg/g), indicating better photosynthetic capacity, while T_1 recorded the lowest (2.18 mg/g). The substantial increase in chlorophyll under INM treatments can be attributed to the combined action of *Azotobacter*, PSB, and humic acid, which improve nutrient uptake, enhance nitrogen metabolism, and stimulate chlorophyll synthesis. Earlier studies by Bhat (2021), and Akash *et al.* (2013) also reported that biofertilizers and humic substances significantly enhance chlorophyll content and photosynthetic efficiency in strawberry and other horticultural crops.

Integrated nutrient management had a significant influence on growth and flowering behaviour in strawberry (Table 2). The number of runners/plant increased consistently with the addition of biofertilizers and humic acid. The maximum number of runners (5.75) was produced under T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed by T_7 (4.24), while the control (T_1) recorded the lowest (2.35). The days to first flowering showed a decreasing trend with improved nutrient management. The earliest flowering was observed under T_8 (42.78 days), indicating accelerated floral initiation due to enhanced nutrient uptake and hormonal activity, whereas the control exhibited the latest flowering (58.54 days). A similar trend was observed for first harvesting, with T_8 recording the earliest harvest (70.24 days) and the control the latest (89.21 days).

Fruit production was also positively influenced by INM treatments. The maximum number of fruits per plant (18.05) was observed in T_8, followed by T_7 (17.41), while the control produced the least (12.51). Fruit set percentage was highest under T_8 (85.00%), indicating improved pollination efficiency and flower fertility, whereas the lowest value was recorded in the control (65.87%). The overall improvement in flowering, runner production, and fruit set under T_8 could be attributed to the synergistic effect of *Azotobacter*, PSB, and humic acid, which enhance nitrogen fixation, phosphorus availability, root vigor, and synthesis of growth-promoting substances. Similar enhancements in strawberry reproductive traits under integrated nutrient management have been reported by Yadav *et al.* (2019), Mohamed *et al.* (2017), Mor *et al.* (2021) and Petre and Selaru (2020).

The physical characteristics of fruits improved noticeably under integrated nutrient management practices (Table 2). Fruit length increased progressively with enhanced nutrient combinations, with the maximum length (4.39 cm) recorded under T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed by T_7 (3.91 cm) and T_6 (3.74 cm), whereas control exhibited the lowest value (2.64 cm). A similar trend was observed for fruit width, where T_8 registered the highest measurement (4.13 cm), followed by T_7 (3.51 cm). The lowest fruit width (2.15 cm) was obtained under the control.

The gradual increase in both fruit length and width across INM treatments reflects better cell expansion and nutrient accumulation influenced by microbial inoculants and humic substances. Fruit weight also improved significantly under integrated nutrient practices. The heaviest fruits (17.46 g) were recorded in T_8, followed by T_7 (16.57 g) and T_6 (15.34 g), whereas minimum fruit weight (10.15 g) occurred in the control. A similar increasing pattern was recorded for fruit volume, with T_8 producing the maximum volume (20.43 ml) compared to the lowest (15.47 ml) in the control treatment. Earlier studies by Kumar *et al.* (2018), Lopez-Garcia *et al* (2016), and Suleiman *et al.* (2021), who reported that the combined application of biofertilizers and organic amendments enhances fruit morphology and marketable yield in strawberry.

Fruit yield showed a remarkable increase with the application of integrated nutrient managemen treatments (Table 2). The maximum fruit yield per plant (575.50 g) was recorded under T_8 (RDF + Azotobacter + PSB + 2% humic acid), followed by T_7 (567.48 g) and T_2 (556.48 g). The lowest yield (526.97 g) was recorded in the control (T_1). This indicates that the combined application of microbial inoculants and humic acid substantially enhances plant productivity. A similar trend was observed for yield per hectare. The highest fruit yield (12.11 t/ha) was produced under T_8, followed by T_7 (11.58 t/ha) and T_6 (10.71 t/ha). The lowest yield (8.17 t/ha) was obtained in the control. The improvement in yield under T_8 can be attributed to enhanced nutrient uptake, improved photosynthetic activity, increased fruit set, and overall better plant health resulting from the combined effects of Azotobacter, PSB, and humic acid. Earlier studies by Wani *et al.* (2013), and Iqbal *et al.* (2008) have similarly reported.

CONCLUSION

Thus, integrated nutrient management using biofertilizers and humic acid along with recommended chemical fertilizers is a sustainable, cost-effective, and environment friendly nutrient strategy for strawberry growers. Adoption of T_8-type INM treatments can significantly enhance strawberry productivity and profitability, especially under semi-arid conditions of Haryana and similar agroclimatic regions.

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Current Horticulture 14(3): 70-73, July–September 2026

Research Article

DOI: 10.5958/2455-7560.2026.00042.7

Received: 5 October 2025; Revised: 18 May 2026: Accepted: 18 May 2026

Relative efficacy of cyclaniliprole against *Helicoverpa armigera* and *Spodoptera litura* on chilli (*Capsicum annuum*)

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Abstract

Field experiments were conducted to study the efficacy of insecticide cyclaniliprole 10% DC at 300, 350, 400, and 450 ml ha^{-1}, along with two standard checks: Chlorantraniliprole 18.5% SC at 150 ml ha^{-1} and Abamectin benzoate 5% SG at 200 g ha^{-1}, against lepidopterous insect pests infesting chilli (*Capsicum annuum* L.) crop at Rajasthan College of Agriculture, Udaipur, during *kharif* 2020 and 2021. Chilli variety, Tanaya, was sown in a randomized block design with seven treatments and four replications. The results showed that cyclaniliprole 10% DC was equally effective at 400- and 450-ml ha^{-1} in controlling fruits-borer (*Helicoverpa armigera*) and tobacco caterpillar (*Spodoptera litura*), and was more effective than other standard treatments. The highest mean yield was recorded in treatment of cyclaniliprole 10% DC at 450 ml ha^{-1}, which was 15.05 t ha^{-1} and 15.26 t ha^{-1} during the respective years, compared to the control.

Key words: Borers, Efficacy, Insecticide, Noval, Cyclaniliprole, Aphids, Thrips

Chilli (*Capsicum annuum* L.) vulnerable to many insect pests, *viz.* aphids (*Myzus persicae* Sulzer., *Aphis gossypii* Glover.), thrips (*Scirtothrips dorsalis* Hood.,), yellow mite (*Polyphagotarsonemus latus* Banks), fruits-borer (*Helicoverpa armigera* Hubner) and tobacco caterpillar (*Spodoptera litura* Fabricius) (Swami *et al.,* 2018[a], Swami *et al.,* 2018[b] and Dangi *et al.,* 2024). Among them fruit-borers *H. armigera* and *S. litura* cause both qualitatively and quantitively losses to chilli crop in considerable amount at fruiting stage. At vegetative stage theses caterpillars defoliate the standing crop and after onset of fruiting the larvae makes round holes on fruits by feeding on pericarp resulting in damaged fruits, decreasing yield up to 40 - 50% (Patel *et al.,* 2016 and Selvanarayanan and Narayanasamy, 2006).

Cyclaniliprole is highly effective against numerous insect pests. Once exposed, through contact or ingestion, Cyclaniliprole attaches to insect RyR inducing the uncontrolled release of calcium stores present in muscle cells. Indiscriminate and extensive use of chemical insecticides in past few decades has led to development of resistance and hence the management of *Helicoverpa armigera* has become increasingly difficult due to development of resistance to most commonly used chemical class of insecticides as reported (Armes *et al.* 1996, Kranthi 1997, Ramasubramaniam and Regupathy 2004). Therefore, study was carried out to find out the bio-efficacy of new molecules against lepidopterous insect pests infesting chilli crop.

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MATERIALS AND METHODS

The experiment was conducted RCA, Udaipur, during *kharif* 2020 and 2021. Chilli Tanaya seedlings were transplanted in plot size of 5 m X 5 m at 50 cm x 50 cm spacing in a randomized block design with seven treatments including one untreated control with four replications. Other package and practice were followed as per university recommendation. Noval insecticide, Cyclaniliprole 10% DC was evaluated at different doses, i.e. @ 300 ml ha^{-1}, 350 ml ha^{-1}, 400 ml ha^{-1}, 450 ml ha^{-1}, compared with two standard checks, i.e. chlorantraniliprole 18.5% SC @ 150 ml ha^{-1} and Emamectin benzoate 5% SG @ 200 g ha^{-1} against lepidopterous insect pests infesting chilli crop. Each treatment was applied twice first when the borer population crossed the ETL (Economic Threshold Level) and second was after 16 days of first spray. Periodic observations for number of larvae and damaged fruits were recorded on 10 randomly selected plants per replication per treatment before and after 5 and 10 days after each spray. The per cent fruit damage reduction over the control as well as per cent reduction in larval population over the control was calculated by using Henderson and Tilton (1952) formula.

RESULTS AND DISCUSSION

The Fruit-borer (*Helicoverpa armigera*) mean population was recorded before first spray and 5 and 10 days after each spray during both the years. Before first spray fruit-borer population was uniform in various treatments since the difference in population was not significant. After spray all the treatments were found significantly effective in controlling fruit-borer population compared to the untreated control. Cyclaniliprole 10% DC @ 450 ml ha^{-1} was more effective at each observation time with low pest population.

Next best treatment in order of effectiveness was cyclaniliprole 10% DC @ 400 ml ha^{-1}, followed by chlorantoniliprole 18.5% SC 150 ml ha^{-1}, emamectin benzoate 5% SG @ 200 ml ha^{-1}, cyclaniliprole 10% DC@ 350 ml ha^{-1} and cyclaniliprole 10% DC @ 300 ml ha^{-1}. The highest fruits borer population was recorded in untreated control. The per cent reduction in fruit-borer population over the control was also calculated (Table-1). The higher population reduction over the control was recorded with cyclaniliprole 10% DC@ 450 ml ha^{-1}, which ranged from 60.03 to 75.06 % and 47.83 to 76.61 % in first and second spray, respectively during *kharif* 2020. While, it was 60.56 to 72.35 % and 60.04 to 73.50 % during first and second spray 5 and 10 days after application, respectively during *kharif* 2021.

The tobacco caterpillar (*Spodoptera litura*) mean population was recorded before first spray and at different time intervals after each spray during first and second seasons. Before first spray, tobacco caterpillar population was uniform in various treatments since difference in population was not significant. After spray all the treatments were found significantly effective in controlling the tobacco caterpillar population compared to the untreated control. Amongst treatments, cyclaniliprole 10% DC @ 450 ml/ha was more effective at each observation time with low pest population (Table 2).

Next treatment in order of effectiveness was cyclaniliprole 10% DC @ 400 ml ha^{-1} followed by chlorantoniliprole 18.5% SC 150 ml ha^{-1}, emamectin benzoate 5% SG @ 200 ml ha^{-1}, cyclaniliprole 10% DC @ 350 ml ha^{-1} and cyclaniliprole 10% DC @ 300 ml ha^{-1}. The highest fruit borer population was recorded in untreated control. The per cent reduction in tobacco caterpillar population over control was also calculated. The higher population reduction over the control was recorded with the treatment of cyclaniliprole 10% DC@ 450 ml ha^{-1}, which ranged from 65.22 to 74.95 % and 58.68 to 74.81 % in first and second spray, respectively during *kharif* 2020. While, it was 65.05 to 74.01 % and 42.92 to 74.34 % in first and second spray, respectively during *kharif* 2021.

Table 1: Evaluation of Cyclaniliprole 10% DC against *H. armigera* on chilli during *kharif* 2020 and 2021

Treatment	Dose (ml/ ha)	PTP	I spray (2020)				II spray (2020)				I spray (2021)				II spray (2021)			
			Mean (larvae10 plant^{-1})		Reduction over control (%)		Mean (larvae10 plant^{-1})		Reduction over control (%)		Mean (larvae10 plant^{-1})		Reduction over control (%)		Mean (larvae10 plant^{-1})		Reduction over control (%)	
			5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS
Cyclaniliprole 10% DC	300	5.15 (0.72)*	0.75 (0.28)	0.70 (0.27)	50.01	53.01	0.9 (0.31)	0.87 (0.30)	33.63	38.12	0.97 (0.32)	0.91 (0.31)	50.71	53.52	0.90 (0.31)	0.84 (0.30)	50.03	53.08
Cyclaniliprole 10% DC	350	5.23 (0.73)	0.70 (0.27)	0.65 (0.26)	53.57	56.56	0.84 (0.30)	1.02 (0.33)	38.88	26.35	0.91 (0.31)	0.85 (0.30)	54.22	57.03	0.84 (0.30)	0.78 (0.29)	53.54	56.59
Cyclaniliprole 10% DC	400	5.43 (0.74)	0.625 (0.26)	0.40 (0.21)	58.24	73.29	0.75 (0.28)	0.40 (0.21)	46.42	71.34	0.81 (0.29)	0.58 (0.25)	58.76	70.85	0.75 (0.28)	0.69 (0.27)	58.27	72.18
Cyclaniliprole 10% DC	450	5.28 (0.73)	0.60 (0.25)	0.38 (0.21)	60.03	75.06	0.72 (0.28)	0.32 (0.19)	47.83	76.61	0.78 (0.29)	0.54 (0.24)	60.56	72.35	0.72 (0.28)	0.67 (0.27)	60.04	73.50
Chlorantraniliprole 18.5% SC	150	5.33 (0.73)	0.65 (0.26)	0.43 (0.22)	56.80	71.70	0.78 (0.29)	0.42 (0.22)	44.24	69.95	0.84 (0.30)	0.61 (0.26)	57.39	69.19	0.78 (0.29)	0.72 (0.28)	56.79	72.06
Emamectin benzoate 5% SG	200g	5.25 (0.73)	0.65 (0.26)	0.45 (0.22)	56.68	69.60	0.78 (0.29)	0.42 (0.22)	43.54	69.45	0.84 (0.30)	0.62 (0.26)	57.21	68.60	0.78 (0.29)	0.75 (0.28)	56.69	70.86
Untreated control	-	5.28 (0.73)	1.60 (0.39)	1.50 (0.39)	-	-	1.8 (0.43)	1.62 (0.41)	-	-	1.95 (0.45)	1.95 (0.45)	-	-	1.80 (0.43)	1.80 (0.43)	-	-
S.Em (±)			0.12	0.19	-	-	0.11	0.22	-	-	0.14	0.15	-	-	0.13	0.14	-	-
CD (5%)		NS	0.26	0.41	-	-	0.24	0.46	-	-	0.30	0.32	-	-	0.28	0.30	-	-

*Values in parentheses are square root transformed values PTP- pretreatment count
NS, non-significant, DAS, days after spray

All the treatment were significantly superior to over the control. The maximum reduction in fruit damage was recorded in cyclaniliprole 10% DC @ 450 ml ha^{-1}, followed by chlorantoniliprole 18.5% SC 150 ml ha^{-1}, emamectin benzoate 5% SG @ 200 ml ha^{-1}, Cyclaniliprole 10% DC@ 350 ml ha^{-1} and cyclaniliprole 10% DC@ 300 ml ha^{-1}. All the treatments recorded maximum and significantly yielded in comparison to the control. The mean maximum yield of chilli was recorded in cyclaniliprole 10% DC @ 450 ml ha^{-1} which was 15.05 t ha^{-1}and 15.26 t ha^{-1}during 2020 and 2021 respectively.

The result of effectiveness of different insecticidal treatments against chilli fruit-borer showed that all the treatments were significantly superior over the control in fruit damage. Cyclaniliprole 10% DC @ 450 15.26 ml ha^{-1}was more effective at each observation time with low pest population and fruit damage. The cyclaniliprole 10% DC@ 300 15.26 ml ha^{-1}was least effective treatment as population reduction of fruit borers and mean fruit damage, as against in untreated control.The mean maximum yield of chilli was recorded in the treatment of cyclaniliprole 10% DC @ 450 ml ha^{-1} which was 15.05 t ha^{-1}and 15.26 t ha^{-1}during 2020 and 2021 respectively in comparison to control.

The results are in close agreement with the findings of Parsanna *et al.,* (2020). The present findings are in conformity with those of Parsanna *et al.,* (2020). Tatagar *et al.,* (2009) reported that among various dosages, flubendiamide 20 WG at 60 gm ha^{-1}recorded highest yield of 0.7 t ha^{-1} with lowest mean fruit damage of 3.45 per cent, followed by flubendiamide 20 WG at 40 g a.i. ha^{-1}(0.6 t ha^{-1}). Flubendiamide 480 SC 125 ml ha^{-1} against brinjal shoot and fruit borer during summer and *kharif* season was reported to be most effective by Ameta *et al.,* (2010^{b}). Sinha and Nath (2012) and Nayaka *et al.* (2018) evaluated the efficacy of five insecticides, viz. spiromesifen (100 g a.i. ha^{-1}), chlorantraniliprole (20 g a.i. ha^{-1}), novaluron (75 g a.i. ha^{-1}), flubendamide (25 g a.i. ha^{-1}) and carbosulfan EC (250 g a.i. ha^{-1}) against insect pests of brinjal. As far as infestation of *Leucinodes orbonalis* was concerned, damage in various treatments ranged 4.0-14.2% as compared to 23.1% of control on weight basis while it ranged from 3.5-12.2% in treatments on number basis it was 20.6% in untreated check.

CONCLUSION

The efficacy of cyclaniliprole 10% DC showed that test product was equally effective @ 450 and 400

Table 2: Evaluation of Cyclaniliprole 10% DC against *S. litura* on chilli during *kharif* 2020 and 2021

Treatment	Dose (ml/ha)	PTP	I spray (2020) Mean (larvae10 plant^{-1})		I spray (2020) Reduction over control (%)		II spray (2020) Mean (larvae10 plant^{-1})		II spray (2020) Reduction over control (%)		I spray (2021) Mean (larvae10 plant^{-1})		I spray (2021) Reduction over control (%)		II spray (2021) Mean (larvae10 plant^{-1})		II spray (2021) Reduction over control (%)	
			5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS	5 DAS	10 DAS
Cyclaniliprole 10% DC	300	5.40 (0.74)*	0.72 (0.28)	0.70 (0.27)	58.02	61.13	0.95 (0.32)	0.80 (0.29)	32.12	42.99	0.85 (0.30)	0.83 (0.30)	57.81	61.10	1.23 (0.36)	0.99 (0.32)	32.16	44.77
Cyclaniliprole 10% DC	350	5.43 (0.74)	0.70 (0.27)	0.65 (0.26)	59.31	64.16	0.90 (0.31)	0.78 (0.29)	35.94	44.63	0.82 (0.29)	0.77 (0.29)	59.13	64.12	1.17 (0.35)	0.90 (0.31)	36.06	50.82
Cyclaniliprole 10% DC	400	5.30 (0.73)	0.62 (0.26)	0.53 (0.24)	63.57	71.10	0.63 (0.26)	0.40 (0.21)	55.40	71.36	0.75 (0.28)	0.55 (0.24)	63.42	73.91	1.07 (0.33)	0.48 (0.22)	41.01	73.64
Cyclaniliprole 10% DC	450	5.30 (0.73)	0.60 (0.25)	0.45 (0.22)	65.22	74.95	0.58 (0.25)	0.35 (0.20)	58.68	74.81	0.70 (0.27)	0.55 (0.24)	65.05	74.01	1.04 (0.33)	0.48 (0.23)	42.92	74.34
Chlorantraniliprole 18.5% SC	150	5.30 (0.73)	0.65 (0.26)	0.55 (0.24)	61.85	69.84	0.68 (0.27)	0.40 (0.21)	51.90	70.71	0.76 (0.28)	0.57 (0.25)	61.73	72.92	1.10 (0.34)	0.55 (0.24)	39.49	69.73
Emamectin benzoate 5% SG	200g	5.28 (0.73)	0.67 (0.27)	0.58 (0.25)	61.06	68.53	0.73 (0.28)	0.43 (0.22)	49.12	69.69	0.75 (0.29)	0.66 (0.27)	60.84	69.10	1.10 (0.34)	0.50 (0.23)	39.39	72.67
Untreated control	-	5.38 (0.74)	1.72 (0.42)	1.83 (0.43)	-	-	1.40 (0.38)	1.40 (0.38)	-	-	2.03 (0.46)	2.15 (0.47)	-	-	1.82 (0.43)	1.82 (0.43)	-	-
S.Em (±)			0.19	0.14	-	-	0.20	0.17	-	-	0.21	0.16	-	-	0.12	0.24	-	-
CD (5%)		NS	0.40	0.30	-	-	0.42	0.37	-	-								

*Values in parentheses are square root transformed values PTP- pretreatment count

NS, non-significant, DAS, days after spray ml ha^{-1} to control fruit-borer (*Helicoverpa armigera*) and tobacco caterpillar (*Spodoptera litura*) on chilli crop and better than other standard treatments. Hence, use of cyclaniliprole 10% DC @ 400 ml ha^{-1} can be suggested for the effective control of fruit-borer and tobacco caterpillar insect pests on chilli crop to avoid resistance in fruit borer (*Helicoverpa armigera*) and tobacco caterpillar (*Spodoptera litura*).

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Research Article

Current Horticulture 14(3): 74-76, July–September 2026

DOI: 10.5958/2455-7560.2026.00043.9

Received: June 24, 2026; Revised: July 2, 2026: Accepted: 4 September 2026

Assessment of tomato (*Lycopersicum esculentum*) varieties for yield and resistance to diseases under Tripura condition

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Abstract

An on- farm trial was conducted by Krishi Vigyan Kendra, Khowai in Khowai district of Tripura during 2021-22 and 2022-23 to study the morphological parameter, yield potential and resistance to tobacco leaf curl virus (TLCV), bacterial wilt (BW) and early blight (EB) on four varieties of tomato (*Lycopersicum esculentum* Mill.), viz. Arka Rakshak, Arka Samrat, Arka Abhed and Trishul (Local check) at farmers' fields. The observations were recorded on plant height (cm), branches/plant, days to first harvesting, number of fruits/plant, average fruit weight (g), fruit length (cm), fruit breadth (cm), and fruit yield/ plant (kg), yeild / ha area, economics and diseases incidence (%). The mean data of all two years were statistically analyzed. The results revealed that maximum number of fruits/plant (40.0) was found in Arka Rakshak and the lowest (36.8) in local check (Trishul) . The maximum average fruit weight (75.37 g) and fruit yield (3.03kg/ plant) was recorded in Arka Rakshak compared to other tomato varieties. The maximum fruit yield (61.06 t/ha) was recorded in Arka Rakshak. The incidence of diseases like tobacco leaf curl virus (0.5 %), bacterial wilt (0%) and early blight (0.97%) were also very negligible in Arka Rakshak. The maximum net profit (Rs. 12,20,000 per ha), B:C ratio (5.5) were recorded in Arka Rakshak as compared to other varieties

Key words: Growth, Yield potential, Resistance, Tobacco leaf curl virus, Bacterial wilt, Early blight

Tomato (*Lycopersicum esculentum* Mill.) is one of the most important Solanaceous vegetables crops after potato. The productivity of tomatoes is comparatively low in India compared to other producing countries in the world (Keshava Reddy *et al.,* 2018). In India, Madhya Pradesh contributes the highest in area and production of tomatoes, accounting for about 11.89 and 14.11 per cent, respectively. This is followed by Odisha (10.85), Tamil Nadu (9.59), Karnataka (7.74), and Andhra Pradesh (7.12%) in area. In Tripura, favorable agroclimatic condition allows the growers to cultivate tomato extensively in *rabi* season owing to huge market demand. This crop is equally grown both in the plains and hills of north-eastern region of India. In Tripura, tomato cultivation covers an extensive area of 2.01 Thousand hectares, resulting in an annual production of approximately 67.92 thousand tonnes with an impressive yield of 33.79 t/ha. In region, major constrains faces by famers is severe yield losses due to Tobacco Leaf Curl Virus (TLCV), bacterial wilt, and early blight. Keeping in view, an on-farm testing was conducted in farmers fields of Khowai district of Tripura during 2021-22 and 2022-23 to assess the performance of some resistant tomato varieties.

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MATERIALS AND METHODS

The experiment was conducted in Krishnapur, an adopted village of Krishi Vigyan Kendra, Khowai, located in the Teliamura sub-division of the Khowai district, is centered at approximately 23°7544′ N latitude and 91°6681′ E logitude. Krishnapur (Teliamura, Tripura) features a warm, humid subtropical climate. It receives an average annual rainfall of about 2,200 mm, heavily concentrated during June-September. The annual average temperature ranges between a minimum of 24° to 25° C and a maximum of 31-33°C. The soil is medium in organic carbon content (0.67 %) and the available nutrient status is low in nitrogen, medium range of phosphorus and potassium status. Five farmers were selected for this study and comprise a total of 20 treatments.

Four varieties, viz. Arka Rakshak, Arka samrat, Arka Abhed and Trishul, a private hybrid (Local check) were taken for the experiment. Arka Rakshak and Arka Samrat are known as triple resistant hybrid, resistant to tomato leaf curl virus (ToLCV), bacterial wilt (BW), early blight (EB), whereas, Arka Abedh is a multiple disease resistant hybrid.

The 30-days-old seedlings of were supplied to the farmers for planting. The transplanting was done in the first week of November during both the years at a spacing of 90 x 60cm, which gives a plant population of around 18,500/ ha. Well-rotten FYM @ 25 MT and NPK @ 80:60:80 kg per ha were incorporated to enrich the soil. Half of the dose of N and K, full dose of P was applied as basal dose at the time of transplanting, whereas other half of N and K were applied as topdressing during flower initiation. Other intercultural operations like weeding, hoeing, staking, irrigation were done as and when required. Various traits, including plant height (cm), branches/plant, days to first harvest, number of fruits/plant, average fruit weight (g), fruit length (cm), fruit breadth (cm) and fruit yield, economics and disease incidences for bacterial wilt (BW), early leaf blight (EB), and tomato leaf curl virus (TLCV) were observed during the assessment. The data were subjected to statistical analysis.

RESULTS AND DISCUSSION

Screening of varieties were conducted for two consecutive years for growth, yield and yield attributes. The data revealed that maximum plant height was in Arka Rakshak (122.34 cm), followed by Trishul (120.51 cm), Arka Samrat (119.21) and Arka Abhed (117 .33) respectively. Maximum no. of branches were observed in Arka Rakshak (9) and lowest was in Arka Abhed (7). Minimum days to first harvest was recorded in Arka Abhed (140 days) whereas Trishul, the local check took maximum days to first harvest (148 days). The number of fruits plant was higher in Arka Rakshak (40.0) and lower was in local check (36.8). Significantly higher average fruit weight was noted in Arka Rakshak (75.37g) followed by Arka Samrat (70.5), whereas lowest was in Trishul (53g). Similarly, maximum fruit length and fruit breath was noticed in Arkra Rakshak. Data demonstrated that maximum yield per plant (3.0kg) and yield per unit area (61.06 t/ha) was in Arka Rakshak followed by Arka Samrat, Arka abhed respectively. In contrast, local check recorded minimum yield per plant (2.4kg) and yield per unit area (52.05t/ha).

The result revealed that higher yield primarily associated with number of fruits plant and the average fruit weight. A positive relation was observed among yield and yield attributing parameters. The better performance of Arka Rakshak could be the suitable agro climatic condition of Tripura. The present findings corroborate those of Singh et al. (2021), who also reported superior yield performance, reduced bacterial wilt incidence and better economic returns of Arka Rakshak under tropical island conditions. The variation in yield among varieties may be due to genetic makeup of different variety (Kumar et al., 2022; Olaniyi and Fagbayide, 1999) as they were grown in the same agro climatic condition with same recommended package of practice. Variation in the different morphological parameter, yield and yield attributes of were also recorded by Rangnamei *et al.*, 2017; Mishra et al., 2024; Reddy et al., 2022; Remzeena *et al.*, 2023; Siva *et al.*,2023; Singh *et al,* 2023.

Table 2: Disease incidence percentage:

Treatment	Blight (%)	TLCV (%)	Bacterial wilt (%)
T_1	0.97	0.50	0
T_2	1.17	1.70	0
T_3	2.03	3.10	5.10
T_4 (Local check)	18.88	7.20	10.20
SEm ±	**0.31**	**0.38**	**0.64**
CD (P=0.05)	**0.96**	**1.17**	**1.97**

Arka Rakshak shows minimum incidence of early blight where as the local check variety Trishul shows up to 18.88% of this disease incidence. Tobacco leaf curl virus was as low as only 0.5% in Arka Rakshak followed by Arka Samrat (1.7%) as compared to the incidence in Local check (7.2%). Similarly, there was no incidence of bacterial wilt in Arka Rakshak and Arka Samrat whereas 5.1 % of incidence was recorded in Arka Abhed, while maximum was in local check (10.2%). These findings coincide with the study of Mishra *et al.,* 2019, Singh *et al.,* 2023, Reddy *et al.,* 2022.

Highest net income (₹1,220,000) was recorded in Arka Rakshak (T1), followed by Arka Samart (₹ 1,160,000). Further, net income and B:C ratio were found maximum (₹1,220,000 ha and 5.5) in Arka Rakshak. Similarly in Arka Abhed Net income of ₹ 1,160,000 and B:C ratio of 5.2 were observed. Whereas, lowest net income and B:C ratio (₹1,040,000/ha and 4.7) was in to the local check. This could be because the Arka Rakshak tomato hybrid had more branches, more fruits plant, more pickings, and a higher yield compared to Local/ check (Table 3).

Table 1: Growth and yield attributes of tomato varieties:

Variety	PH (cm)	BPP	DFH (d)	NFPP	AFW (g)	FL (cm)	FBr (cm)	YPP (kg)	YH (t ha^{-1})
T_1	122.34	9.00	144.00	40.00	75.37	6.50	7.00	3.03	61.06
T_2	119.21	8.00	146.00	39.00	70.50	5.50	6.30	2.80	57.20
T_3	117 .33	7.00	140.00	38.50	65.00	5.80	5.90	2.60	55.22
T_4	120.51	8.00	148.00	36.80	53.00	5.60	5.80	2.40	52.05
SEm ±	0.58	0.22	0.95	0.48	1.05	0.12	0.11	0.07	0.82
CD (P=0.05)	1.80	0.67	2.94	1.48	3.25	0.38	0.33	0.28	2.53

PH = Plant height; BPP = branches per plant; DFH = days to first harvest; NFPP = number of fruits/plant; AFW = average fruit weight; FL = fruit length; FBr = fruit breadth; YPP = yield/plant; YH = Yield/ha.

Table 3: Economics of tomato hybrids (1 ha):

Treatment	Gross cost (Rs)	Gross income (Rs)	Net income (Rs)	B:C ratio
T_1	271,111	1,491,111	1,220,000	5.5
T_2	276,190	1,436,190	1,160,000	5.2
T_3	278,049	1,418,049	1,140,000	5.1
T_4 (Local Check)	281,081	1,321,081	1,040,000	4.7

CONCLUSION

Thus, it can be concluded that tomato var. Arka Rakshak was found suitable in terms of various yield and yield-attributing parameters, followed by Arka Samrat under the agroclimatic condition of Khowai District of Tripura. Moreover, Arka Rakshak shows less incidence of major diseases and thus contributes to higher B:C ratio. Hence, Arka Rakshak variety can be adopted by the farmers.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Krishi Vigyan Kendra (KVK), Khowai, Tripura, in conducting this The authors also thank the Director, ICAR-ATARI Zone VI, Barapani, Meghalaya, for financial and institutional support.

Conflict of Interest Statement

The authors declare no conflicts of interest

Funding sources

The programme was funded by ICAR-ATARI Zone VI, which provides financial support for KVK research and extension activities.

Author Contributions

Author 1 conceived and conducted the study, collected and analyzed the data, and prepared the manuscript. Author 2 provided overall guidance, supervised the research activities, and reviewed and approved the final manuscript. All authors have read the manuscript and agreed to its content. Author 3 has done the statistical analysis of the raw data. They have also approved the final version of manuscript and consent to its submission

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Research Article

Current Horticulture 14(3): 77-81, July–September 2026

DOI: 10.5958/2455-7560.2026.00044.0

Received: August 1, 2026; Revised: 4 September 2026: Accepted: 4 September 2026

Microbial fortification of sweet orange *(Citrus sinensis)* rhizosphere for improvement in soil health indicators

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Abstract

The effect of application of rhizosphere microbial consortium on biological properties of soils from sweet orange [*Citrus sinensis* (L.) Osbeck] was studied through controlled pot as well as field experiment. The results revealed that growth media comprising rhizosphere soil of *Ficus* species was slightly acidic to neutral in pH, loaded with organic carbon and reduced level of lime. While, the *Umber* rhizosphere soil recorded high available N, P, K, S and micronutrients, coupled with biological properties of soils, marked by high bacterial, fungal and actinomycetes counts. Soils from three Ficus species, viz. *Ficus racemosa* L. *Ficus religiosa* L. and *Ficus benghalensis* L. were hybridized together in equal proportion and incubated for development of beneficial microbial consortia. This hybridized soil was observed developing significant improvements in SMBC (soil microbial biomass carbon) and SMBN (soil microbial biomass nitrogen), coupled with reduced CO_2 evolving enzymes. The developed *Ficus* species-based rhizosphere soil consortia with recommended doses of NPK showed significant improvements in soil quality parameters, nutrient availability index and an enhanced fruit yield with desirable fruit quality parameters.

Key words: Rhizosphere, Consortium, *Ficus racemos, Ficus religiosa, Ficus benghalensis,* Microbial biomass nutrients, CO_2 evolution, Enzymes

The rhizosphere refers to soil region nearest to plant root system, and is characterized by a high microbial activity (De Ridder *et al.,* 2005). Roots release a large quantity of metabolites from living root hairs or fibrous root systems into the rhizosphere (Nihorimbere *et al.,* 2011). The rhizosphere inhabits millions of microorganisms, such as bacteria and fungi, which compete for water, nutrients and space, and sometimes improve their competitiveness by developing an intimate association with plant (Baar, 2010). Citrus crop offers a strong sink for sequestration of atmospheric carbon dioxide, thereby, aid in moderating the impact of climate change-related issues, besides creating a parallel nutrient sink (Srivastava *et al.,* 2000 ; Srivastava and Singh, 2008). The paradigm shifts from purely inorganic to either organic fertilizers or in combination with chemical fertilizers and microbial inoculants (preferably in consortium mode) started gaining wide scale use for enhanced soil health vis-à-vis elevated quality production and reduced rhizosphere CO_2 emission (Srivastava, 2018). This conceptual change later formed the basis for integrated soil fertility management (ISFM)-based strategy involving three basic components, viz. microbial inoculants (biofertilizers), inorganic fertilizers and organic fertilizers (Srivastava *et al.,* 2022).

Development of microbial consortium exploiting the microbial synergisms with variety of fruit crops as an important component of ISFM is one of the popular methods of managing multiple soil fertility constraints occurring within the rhizosphere (Hota *et al.,* 2020). Upscaling such studies through rhizosphere hybridization has provided some initial inroads in harnessing the potential of different rhizosphere microbial communities (Srivastava *et al.,* 2009; 2025). ISFM studies carried out in fruit crops in India, Iran, and China showed better agronomic response and soil health-related properties, considered very close to climate-resilient soil fertility management, a gateway to sustainable quality production. According to (Srivastava *et al.* 2021), direct plant growth promotion may result either from improved nutrient acquisition and/or from hormonal stimulation. The soils of central India are mostly derived from basaltic parent material and are commonly deficient in multiple nutrients, including N, P, Fe, Mn, and Zn (Srivastava and Singh, 2004). That is why, the conventional nutrient management strategy mainly based on macronutrient application in citrus orchards has not been very successful in raising the productivity level of citrus (Srivastava *et al.,* 2006).

Yield potential of every citrus variety is based on how well, a particular species adapts on a given soil type, both with respect to available supply of nutrients and associated segregation of microbial communities

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within the rhizosphere (Srivastava and Singh., 2008; Srivastava *et al.,* 2009). A still bigger question emerges, whether rhizosphere competent microbes could collectively contribute towards improved resilience of plant's rhizosphere. Our earlier studies have shown that rhizosphere effective microbes have the tendency to play multiple roles (Keditsu and Srivastava, 2014) to overcome various biotic and abiotic stresses while, interacting with an environment. In this background, incise efforts have been made to analyze various aspects of nutrient-microbe synergy in giving the desired fillip to the productivity' of sweet orange through rhizosphere bio-fortification .

MATERIALS AND METHODS

The importance of rhizosphere microbial population for maintenance of root health, nutrient uptake and tolerance of environmental stress was now well recognized. However, rhizosphere soils of some sacred tree species are yet to be tested for its biotic population or varieties. The site of experiment lies between 19^0 to 20^0 north latitude and 75^0 20" to 77^0 30" east longitude. As many seven treatments, viz., T_1 (NPK + Control as no microorganisms), T_2 (NPK +*Ficus religiosa* L. as PRS at 60 kg/tree), T_3 (NPK + *Ficus benghalensis* L. as BRS at 60 kg/tree), T_4 (NPK + *Ficus racemosa* L. as URS at 60 kg/ tree), T_5 (NPK + mix from 3 *Ficus* species rhizosphere soil at 20 kg each/ tree + 20 kg PRS +20kg BRS + 20 kg URS) ,T_6 (without NPK mix of 3 *Ficus* species rhizosphere soil at 20 kg each/ tree +20 kg PRS +20kg BRS + 20 kg URS)) and T_7 (NPK + dose of *Azotobacter* at 100 gm /tree +PSB as phosphorus solubilising bacteria at 100 gm /tree) + *Trichoderma* at 100 gm /tree) replicated four times were tested 15-years-old orchard . The treatments were tested for their performance on wilting sweet orange trees using RDF (NPK 800:400:400 gm/tree). Half dose of fertilizer was applied at the time of application of rhizosphere soil as basal application nand the remaining half dose was applied at 187-days after basal application.

The soil samples were collected after treatment of 270 days from selected sweet orange orchard in the farmer field. Composite soil sample 0 -20 cm depth were collected from four to five spots and peripheral area or perimeter of each tree, per orchard depending on the area. (Srivastava *et al.,* 1994; Srivastava and Singh , 2004)). The soils samples thus collected by adopting quartering process. Finally, about 1 kg sample was kept for processing. The samples were then placed in clean cloth bags, labeled properly and brought to laboratory. The soil samples after drying in shade were ground with wooden mortar and pestle, pass through 2 mm and 0.5mm sieves and kept in clean polythene bags with proper labeling.

The microbial count of soil was estimated as per recommended procedure as suggested by Pramer and Schmith (1964). While, soil microbial biomass carbon (SMBC) and soil microbial biomass nitrogen (SMBN) were estimated using chloroform fumigation method using the methods as suggested by Jenkinsons and Powlson (1976). Soil enzymes (Dehydrogenase, acid phosphatase and alkaline phosphatase) were determined colorimetrically as per procedure suggested by Chhonkar (2003). The microbial decomposition rate was estimated using in-situ CO_2 evolution rate as described by Chhonkar (2003).

RESULTS AND DISCUSSION

Response on rhizosphere microbial load and microbial biomass nutrients

The application of various rhizosphere soils significantly influenced the microbial population of the sweet orange rhizosphere, with the treatment receiving three *Ficus* species rhizosphere consortia with recommended dose of NPK (T_5) out yielded and showed maximum population of bacteria, fungi and actinomycetes (Table 1). The second best treatment was application of three *Ficus* species rhizosphere consortia in absences of chemical fertilizer application (i.e. without recommended dose of NPK) as T_6. Further scrutiny of data revealed that among three *Ficus* species *Ficus racemosa* L. showed highest population of bacteria, fungi and actinomycetes (T_4). The microbial population over a period of sweet orange growth depicted that in the treatment (T_5), application of rhizosphere consortia tended to increase the microbial population up to 180-days (data not presented). However, at 270- days (at harvesting) the biological population viz., bacteria, fungi and actinomycetes was reduced.

The increase in microbial population due to individual rhizosphere soil and consortia with and without recommended dose of NPK was accountable to favorable microclimate induced by stimulated exudation of organic substances from roots (Wu *et al.,* 2014). Preferable increase in Gram negative bacteria in root zone of many plants over *Azotobacter* and *Actinomycetes* were also reported. The results of this study aligned with observations of Subbarao (2001) reporting the presence of higher fungal colonies in the rhizosphere soil than in the bulk soil of *Ficus* species. Hence, out of different rhizosphere microbial communities, higher fungal count and bacterial counts were observed within the rhizosphere of sweet orange.

The SMBC and SMBN contents were observed significantly affected by different rhizosphere soil treatments , with or without recommended doses of NPK (Table 2). The application of rhizosphere soil consortia (comprising rhizosphere soil of *Ficus*

Table 1: Response of different treatments on microbial load (Bacterial, fungi and actinomycetes population) and soil microbial biomass nutrients (SMBC and SMBN) in rhizosphere of sweet orange

Symbol	Treatments	Bacteria (CFU x 10^7 /g soil)	Fungi (CFU x 10^4 /g soil)	Actinomycetes (CFU x 10^5 /g soil)	SMBC (µg / g soil)	SMBN (mg /kg)
T_1	NPK	38.00	5.00	10.00	178.27	13.42
T_2	NPK + (PRS)	123.25	14.25	41.75	357.74	32.56
T_3	NPK + (BRS)	133.00	16.00	54.00	432.40	36.70
T_4	NPK + (URS)	158.25	21.25	62.00	567.53	41.60
T_5	NPK + Consortia	182.00	30.50	69.00	702.48	55.34
T_6	Without NPK + Consortia	164.25	23.00	66.25	687.45	48.32
T_7	NPK + dose of *Azoto* + *PSB* + *Tricho*	149.50	30.00	63.50	268.59	31.73
	S.Em.±	3.04	0.37	0.63	10.82	0.77
	C.D. at (5%)	9.02	1.09	1.86	32.15	2.28

racemosa L. rhizosphere soil, *Ficus benghalensis* L. and *Ficus religiosa* L.) applied either individually or in combination improved the SMBC and SMBN. The maximum increase in SMBC and SMBN was noticed with treatment T_5 (recommended dose of NPK + consortia) at all the stages of growth observation, including after 270-days of treatments. The second best treatment was T_6 (without recommended dos of NPK+ consortia). Among *Ficus* species once again *Ficus racemosa* L. (URS) proved superior to rest of the treatments, involving either BRS or PRS , with regard to SMBC and SMBN. Improvement in SMBC and SMBN in the sweet orange rhizosphere could be described to increased microbial population with rhizosphere soil rich in nutrients and varied microbial communities as baseline load. The rhizosphere microbial consortia significantly improved soil health indicators. Specifically, this combination of three rhizosphere soil led to a higher SBMC and SMBN , coupled with higher plant available nutrients, duly supported by higher canopy volume and fruit yield of acid lime compared to conventional inorganic fertilizer application .

Response on CO_2 evolution and rhizosphere enzymes profile

The application of URS (*Ficus racemosa* L.), BRS (*Ficus benghalensis*) and PRS (*Ficus religiosa* L.) rhizosphere soil either applied individually or in combination increased the CO_2 evolution to varying proportions (Table 2). The highest CO_2 evolution was found in T_5 (recommended dose of NPK + consortia) at all growth observations, including 270-days of treatment. Such coordination emerging out of plant-soil interactions is extensively mediated by rhizosphere processes, including plant nutrient acquisition (Uren and Reisennur, 1988), root colonization by rhizosphere organism (Baker, 1991), and soil organic matter decomposition (Cheng and Coleman, 1990). Understanding the rhizosphere processes in relation to effects of increased CO_2 concentration is important for predicting the response of soil fertility variations and organic matter to rhizosphere micro-environment of sweet orange.

The CO_2 evolution activity or soil respiration is a key indicator of microbial activity, where microbial communities oxidize organic matter for energy (Wu *et al.,* 2014). Application of only NPK gradually increased CO_2-evolution due to insufficient organic carbon available from microbes; whereas increased CO_2-evolution in other treatments showed sufficient organic carbon available for growth and development of microorganism up to 180-days (data not presented). At late stages, availability of low quantity of organic carbon, recalcitrant phenolic compounds such as lignin and tannin further inhibit microbial activity, slowing the rate of decomposition and mineralization of soil organic matter (Srivastava, 2013; 2023).

Amongst all treatments significantly higher acid phosphatase and alkaline phosphatase activity was recorded in T_5 (NPK + consortium) followed by T_6 (without NPK+ Consortium), T_7, (NPK+ Dose of *Azoto.* + *PSB* + *Tricho*), T_4 (NPK+URS), T3 (NPK +BRS) and T2 (NPK+ PRS). The similar results were also noted in respect of dehydrogenase activity. It varied between 149.68 to 126.93 (ug TPF/gm of soil per 24 hours). Response of different treatments on CO_2 evolution rate, acid phosphatase , alkaline phosphatase and dehydrogenase activity in rhizosphere of sweet orange is due to biogeochemical decomposition process of organic matter rich in exudates and nutrient content to boost activities of different soil enzymes (Miki and Kondoh, 2002; Reich *et al.,* 2005). Further, rhizosphere soil as a top soil rich organic carbon (Venkatesan and Senthurpandian 2006), enzyme activities remain on the higher side, as previously reported (Kandeler *et al.* 2002; Ngullie *et al.,*2015).

Table 2: Response of different treatments on Co_2 evolution rate

Symbol	Treatments	CO_2 evolution activity (mg /100 g soil 24 /hr)	Acid phosphatase activity (µg p-NP g^{-1} soil /hr)	Alkaline phosphatase activity (µg p-NP g^{-1} soil /hr)	Dehydrogenase activity (µg TPF/ gm of soil /24 hr)
T_1	NPK	85.74	28.24	96.42	41.32
T_2	NPK + (PRS)	318.53	90.68	163.38	89.48
T_3	NPK + (BRS)	492.45	96.76	172.51	106.58
T_4	NPK + (URS)	685.15	109.52	186.09	147.78
T_5	NPK + Consortia	745.15	148.26	232.55	193.16
T_6	Without NPK + Consortia	714.13	138.64	216.45	178.44
T_7	NPK + dose of *Azoto + PSB + Tricho*	329.34	106.70	172.69	131.72
	S.Em.±	15.43	3.09	3.09	3.09
	C.D. at 5 (%)	45.85	9.17	9.17	9.17
	Mean	481.50	102.69	175.73	126.93

Acid phosphatase (ACP) and alkaline phosphatase (ALP) are primary enzymes secreted by microorganisms (e.g. *Bacillus, Pseudomonas*) and plant roots to hydrolyze organic phosphorus. ACP is more abundant in acidic soils; while ALP thrives in neutral-to-alkaline soils. Therefore, the concept of integrated nutrient management significantly influences microbial populations and dehydrogenase activity.

Enzyme activities are generally higher in the rhizosphere due to increased microbial activity driven by root exudates. The rhizosphere characterized by secondary metabolites providing a load-supporting functional dichotomy through elevated nutrient-supply, activated soil enzyme profiles, and improvements in root-shoot systems and plant defense enzymes (Srivastava *et al.,* 2025). These response trades-offs collectively contributed to higher quality yield coupled with possibly a better shelf life of fruit (not studied). Three *Ficus* species viz., *Ficus racemosa* L. 2. *Ficus religiosa* L. and *Ficus benghalensis* L. hybridized together in equal proportion and incubated for development of beneficial microbes Consortia, along with recommended dose of NPK , hence showed significant multiple impacts on improvements in fruit yield and quality of sweet orange fruits. These studies provided some useful insights about the concept of rhizosphere hybridization in accost effective and environment effective manner.

ACKNOWLEDGEMENTS

The authors express sincere thanks to Prof. (Dr) V.D. Patil, Ex Dean VNMKV, Parbhani (M.S), Dr Papita H, Gourkhede Assistant Professor, VNMKV, Parbhani and Dr Chetana M. Jagtap, Assistant Professor, Bharti Vidyapeeth, Loknete Mohanrao Kadam College of Agriculture, Hingangaon, Sangali (Maharashtra) for valuable guidance time to time.

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Current Horticulture 14(3): 3-15, July–September 2026
Research Article
DOI: 10.5958/2455-7560.2026.00045.2
Received: 6 February 2024; Revised: 10 May 2026: Accepted: 4 September 2024

Response of cauliflower (*Brassica oleracea*) to different doses of boron and molybdenum on growth, yield and quality in Bundelkhand region

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Abstract

The response of cauliflower (*Brassica oleracea* L. var. *botrytis*) cv. Pant Shubra to different doses of boron and molybdenum on its growth, yield and was conducted at, Research Farm, RLBCAU, Jhansi (Uttar Pradesh) during 2020-21. The treatments comprised application of boron in the form borax @ 10 and 20 kg/ha and molybdenum in the form of ammonium molybdate (A.M.) @ 1 and 2 kg/ha along with RDF (100:60:80). All treatments were allotted as per randomized block design. The plant height, number of leaves, leaf length, leaf width, stem girth, plant spread and leaf area, number of days to curd initiation, number of days to curd maturity, curd diameter, fresh weight of curd, yield/plot and yield/ha. Among all the treatments, T_6 (borax @ 20 kg/ha + ammonium molybdate 2 kg/ha + RDF) was found to be significant. Cauliflower quality components such as chlorophyll content, T_8 (ammonium molybdate 2kg/ha) was found to be the best, T_5 (borax @ 20 kg/ha + ammonium molybdate 1 kg/ha + RDF) recorded the highest TSS, and T_6 (borax @ 20 kg/ha + ammonium molybdate 2 kg/ha + RDF) was significant for protein content, ascorbic acid content, and dry matter content. In grading of curds, the highest A-grade curds were observed in T_6. Among all treatments, the maximum net income and B: C ratio were observed in T_6 (borax @ 20 kg/ha + ammonium molybdate 2 kg/ha + RDF). Therefore the application of borax @ 20 kg/ ha and ammonium molybdate @ 2 kg/ha along with RDF was found to be best treatment for Bundelkhand conditions of Jhansi.

Key words: Curd, TSS, Boron, Molybdenum, Yield, Quality, Protein, Ascorbic acid

Cauliflower (*Brassica oleracea* L. var. *botrytis*), a biennial crop, belongs to family Brassicaceae (Cruciferae) with diploid chromosome number 2n = 2x=18. Cauliflower requires very high amount of macronutrient and micronutrients for better development and quality curd production (Ningawale *et al.,* 2016). Boron is extremely vital to plants (Warington, 1923) and its concentration in soil and irrigation water is a key predictor of agricultural output (Tanaka and Fujiwara, 2007). Jakhar *et al.* (2018) reported that application of boron @ 2.5 kg/ha improves yield, quality and provides early crop in cauliflower. Molybdenum (Mo) is one of the important micronutrient.

The Mo application could promote the growth of Chinese cabbage, increase its yield, raise the contents of chlorophyll, and could change the leaf colour to dark green (Nie *et al.,* 2018). Mo application generally increased curd weight and diameter in cauliflower (Kotur 1995), Molybdenum deficiency in cauliflower causes a distorted growth point, which prevents the development of a head, as well as leaf blades that are primarily made up of midribs, which is known as whip tail of cauliflower (Sharma, 2002). Although boron and molybdenum sole application benefits the plants, but combined application was found to be more beneficial in terms of growth, yield and quality of cauliflower. The highest plant growth, yield/ ha and dry matter content ratio was found in combined application of borax@ 10 kg/ha + ammonium molybdate@ 1 kg/ha (Ningawale *et al.,* 2016). Singh *et al.* (2017) also reported that combined application of borax @ 20 kg/ ha + ammonium molybdate @ 2 kg/ha + RDF recorded the maximum plant height (60.95 cm) and width of leaf (20.24 cm). Pankaj *et al.* (2018) reported that combined application of boron 2 kg/ha + Mn 2.5 kg/ha + Zn 3 kg/ha recorded highest yield, TSS (8.80 Brix), and Vitamin-C (94.80 mg/100g). Therefore trail was conducted to find out suitable dose of boron and molybdenum for improved growth, yield and quality of cauliflower in Bundelkhand region.

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MATERIALS AND METHODS

The experiment was conducted at Research Farm of the RLBCAU, Jhansi (Uttar Pradesh), during *rabi* 2020-21 (November-January). The maximum temperature was 26.7 ^{0}C and minimum temperature 5.2 ^{0}C. The soil sample was taken before transplanting and nutrient status of soil was determined and found that it was a clay loam soil having pH 6.8, organic carbon content is 0.45%, electric conductivity is 0.29 dS/m and N, P and K content is 232.2, 15.1 and 254.1 kg/ha respectively.The experiment consisted of 10 treatments of borax and ammonium molybdate. The doses of 10 and 20 kg/ha of borax and 1 and 2 kg/ha of ammonium molybdate was taken. These doses of borax and ammonium molybdate were allotted into ten treatments as:1) T_1-10kg/ha Borax + 0kg/ha ammonium molybdate + RDF 2)T_2-10 kg /ha borax + 1kg/ ha ammonium molybdate + RDF 3)T_3 -10kg /ha borax

+ 2kg/ha ammonium molybdate + RDF 4)T_4 -20kg/ha borax + 0kg/ha ammonium molybdate + RDF 5)T_5 -20kg/ha borax + 1kg/ha ammonium molybdate + RDF 6) T_6 -20kg/ha borax + 2kg/ha ammonium molybdate + RDF 7) T_7 -0kg/ha borax + 1kg ammonium molybdate+ RDF 8) T_8 -0 kg /ha borax + 2kg/ha ammonium molybdate + RDF 9) T_9 -RDF 10) T_{10} -control.

The cauliflower cv. Pant Shubra seeds were sown in nursery bed on 15th October 2020. The experimental field was ploughed 2-3 times using tractor drawn-cultivator followed by one cross harrowing with a tractor-drawn harrow. The FYM @ 200 q/ha was uniformly applied during final ploughing and then field was levelled using leveller. The healthy seedlings of 25 days old were transplanted in straight line with a distance of 60 cm (row-to-row) and 45 cm (plant-to-plant). Following the transplanting, a light irrigation was applied, with subsequent irrigation continuing every 10-12 days, weed control was carried out by 2-3 hand weeding and earthing up was done after 6 weeks of transplanting, which is very important because earthing-up provide good anchorage for developing curd.

The plant height, number of leaves, leaf length, leaf width, girth of stem, leaf spread, and leaf were recorded 30, 45 and 60 days after transplanting (DAT). The days to curd initiation from transplanting (days), days to curd maturity from initiation (days), diameter of curd (cm), fresh weight of curd (kg), yield (kg/plot) and yield (kg/ha) were recorded. The grading of curd as 'A' grade curd > 15 cm diameter, 'B' grade curd 10-15 cm diameter and 'C' grade curd < 10 cm, curd diameter (cm), dry matter content (%), TSS, ascorbic acid content (mg/100g), protein content (%), chlorophyll content (mg/100g) were recorded.

RESULTS AND DISCUSSION

The significant plant height was recorded, T_6 at 30 (44.20 cm), 45 (56.47 cm) and 60 (62.53 cm) DAT. The minimum plant height was recorded in T_{10} (control). The maximum stem girth was recorded in T_6, the stem girth recorded by T_6 (1.55cm, 3.11 cm and 5.19 cm at 30, 45 and 60 DAT respectively) and it was followed by T_5 and T_3 (Table 1). The minimum stem girth was recorded by T_{10} (control). The plant spread recorded at 30 (37.00 cm), 45 (59.07 cm) and 60 (68.52 cm) DAT revealed that application of Borax @ 20 kg/ha + A.M. @ 2kg/ha + RDF (T_6), recorded the maximum plant spread and it is closely followed by T_2, T_5 and T_3 (Table 1) whereas, lowest plant spread was recorded under T_{10} (control).

The number of leaves recorded by T_6 (Borax @ 20 kg/ha + A.M. @ 2kg/ha + RDF) was found to be significantly superior over all treatments. The minimum number of leaves recorded by the T_{10} (control) Fig. 1. The maximum leaf length of 37.20 cm, 45.25 cm and 52.58 cm at 30, 45 and 60 DAT respectively, recorded by T_6 and minimum leaf length was recorded by T_{10} (Table 1). The maximum leaf width at 30 (15.87 cm) and 60 (28.78 cm) DAT was recorded by T_6 and at 45 DAT, T_5 (21.53 cm) recorded maximum leaf width and minimum was recorded by T_{10} (Table 1). Among all the treatment, the maximum leaf area at 30 and 60 DAT 0.59 and 1.51 cm^2 respectively, was recorded by T_6 and at 45 DAT by T_5 (0.97 cm^2). The leaf area recorded by remaining treatments was identical to each other and significantly minimum leaf area was recorded by T_{10}, control.

The results in accordance with Singh *et al.* (2017) reported that height of plant, number of leaves, leaf width and leaf length increased significantly by application of boron and molybdenum on cauliflower. Treatment T_{12} (borax 20 Kg/ha + sodium molybdate 2kg/ha) has highest 60.95 cm plant height, number of leaves (21.35), leaf width (20.24 cm) and leaf length (51.85), whereas lowest was recorded in control. Kumar *et al.* (2010) reported maximum no. of leaves (21.80), leaf length (51.90cm) and leaf width (19.98 cm) under the soil application of borax @ 20kg/ha + sodium molybdate @ 2kg/ha along with 120: 60: 60 kg/ha. Ningawale *et al.* (2016) reported that highest stem girth (5.14 cm) was recorded in case of T_9 (borax @10 kg+ ammonium molybdate @1 kg/ha) followed by T_{12} (borax @20 kg+ ammonium. molybdate. @ 2kg/ha) soil application and both treatments were at par. stem girth (5.12 cm).

The significantly lowest stem girth (4.50 cm) was recorded in control (T_1). Moniruzzaman *et al.* (2007) reported that maximum plant spread (72.60 cm) of broccoli was recorded under $B_{1.5}$ (boron @ 1.5 kg/ha). Whereas, minimum plant spread (60.78 cm) was recorded under B_0 (control). Taheri *et al.* (2020) reported maximum plant height (36.33 cm), maximum plant spread (57.42 cm) were recorded T_8 (foliar application of zinc and boron @ 1%) and the lowest result for these parameters were found in To (control). Ranjan *et al.* (2019) showed that application of micronutrients (B, Mo and Zn) helped in increasing the stem diameter (3.32 cm) of cauliflower.

The days required for curd initiation and curd maturity of cauliflower responded significantly to different doses of borax and ammonium molybdate. The data regarding number of days to curd initiation in cauliflower revealed that T_6 was found to be early in curd initiation, followed by T_2, however T_6 had a significant edge over T_2 (Table 2) and late curd initiation was recorded in control (T_{10}). Similarly, the number of days required for curd maturity from initiation is significantly minimum in T_6, and it is closely followed by T_5, T_4 and T_3 (Table 2), and T_{10} was found to be the late maturing among all treatments.

The maximum curd diameter was recorded under T_6 and it is followed by T_5 (Table 2), and minimum curd diameter was recorded under T_{10} (control). The maximum fresh weight of curd was recorded under T_6, followed by T_5 and T_4 and all three treatments were on par. The minimum fresh weight was recorded under T_{10} (control). The yield recorded by T_6 was significantly superior among all the treatments followed by, T_5 and minimum yield per plot among all treatments was recorded under T_{10} (control). The maximum yield per ha was recorded by T6 and it was closely followed by T_5 and T_4. The minimum yield was recorded under T_{10} (control).

The findings were in agreement with Ningawale *et al.* (2016), and Kumar *et al.* (2010) reported maximum yield (285.82 q/ha) of cauliflower under T_{12} (borax 20 kg/ha + sodium molybdate 2kg/ ha). Similar kind of results with respect of yield of cauliflower also reported by Singh *et al.* (2017) who stated that, application of borax 20 kg/ha + sodium molybdate 2kg/ha (T_{12}) has recorded the highest yield of 254.63 q/ha and Mori *et al.* (2020) also reported that the highest yield were observed under combined application of Zn, B and Mo in cauliflower.

The cauliflower curds were graded according to their diameter as, A->15 cm, B-10 to 15 cm and C-<10 cm. The data regarding the grading of curds (Table 2) revealed that the highest percentage of A and B grade curds were recorded under T_6 and highest percentage of C grade curds were recorded under T_{10}. The data regarding the chlorophyll content, TSS, protein content, ascorbic acid content revealed that there was significant effect of borax and ammonium molybdate on cauliflower quality. The maximum chlorophyll content was recorded under T_8 and the minimum was recorded under T_{10}. The highest TSS was recorded under T_5 and it was closely followed by T_6 and the lowest TSS was recorded under T_{10}. The protein content recorded by T_6 was significantly superior over all treatments and it was nearly followed by T_5, and the significantly minimum protein content was recorded under T_{10}. Ascorbic acid content recorded by T_6 was the highest and significant among all treatment and it was followed by T_3 (Table 2), the minimum ascorbic acid content among all treatments was recorded under T_{10} (control).

Pankaj *et al.* (2018) observed higher ascorbic acid (87.68 mg/100g) under B + Mo treatment than control in sprouting broccoli and also reported that enhanced TSS content in broccoli can be achieved by combined application of (B + Mn + Zn), Thapa *et*

Table 1: Effect of borax and ammonium molybdate on morphological characters of cauliflower

Treatment	Plant height (cm)			Stem girth (cm)			Plant spread (cm)			Number of leaves			Leaf length (cm)			Leaf width (cm)			Leaf area (m^2)		
	Days after transplanting			Days after transplanting			Days after transplanting			Days after transplanting			Days after transplanting			Days after transplanting			Days after transplanting		
	30	**45**	**60**	**30**	**45**	**60**	**30**	**45**	**60**	**30**	**45**	**60**	**30**	**45**	**60**	**30**	**45**	**60**	**30**	**45**	**60**
T_1 (borax @10 kg/ha+ RDF)	37.73	41.58	53.83	1.38	2.33	4.52	45.53	52.00	64.17	13.27	16.50	17.13	33.33	38.03	44.10	13.57	18.97	21.50	30	45	60
T_2 (borax @ 10 kg/ha + A.M. 1 kg/ ha + RDF)	36.80	44.50	52.83	1.32	2.52	4.92	40.07	48.23	67.17	11.67	15.61	15.61	30.73	38.58	47.40	12.57	18.13	24.33	0.45	0.72	0.95
T_3 (borax @ 10 kg/ha + A.M. 2 kg/ ha + RDF)	36.23	44.52	57.73	1.42	2.66	4.87	45.47	52.63	65.65	12.87	16.58	16.63	30.80	41.43	44.98	13.47	19.68	21.47	0.39	0.70	1.15
T_4 (borax @ 20 kg/ha +RDF)	40.23	45.17	55.40	1.39	2.83	4.75	41.40	51.23	64.37	12.93	16.75	16.50	32.13	41.07	46.50	13.00	20.37	22.60	0.42	0.82	0.96
T_5 (borax @ 20 kg/ha + A.M. 1 kg/ ha + RDF)	39.63	53.58	58.62	1.42	2.97	5.03	46.07	55.03	67.07	13.73	17.87	17.93	32.93	43.60	50.33	14.93	23.00	27.85	0.42	0.84	1.05
T_6 (borax @ 20 kg/ha + A.M. 2 kg/ ha + RDF)	44.20	56.47	62.53	1.55	3.11	5.19	51.00	59.07	68.52	14.95	18.42	18.50	37.20	45.25	52.58	15.87	21.53	28.78	0.49	1.00	1.40
T_7 (A.M. @ 1 kg/ha + RDF)	38.90	49.67	54.43	1.32	2.37	4.93	43.00	54.27	63.77	12.40	15.50	15.58	32.67	40.03	44.65	14.90	20.90	22.70	0.59	0.97	1.51
T_8 (A.M. @ 2 kg/ha + RDF)	41.60	42.83	50.73	1.49	2.38	4.8	45.24	51.80	58.77	11.90	14.92	15.26	31.13	41.62	46.93	15.47	21.08	26.37	0.49	0.84	1.01
T_9 (RDF)	37.63	41.25	50.53	1.33	2.13	4.54	42.87	50.33	58.20	12.20	15.98	16.08	30.30	37.03	44.05	14.93	19.28	21.67	0.48	0.88	1.24
T_{10} (control)	33.23	37.53	42.62	1.33	1.92	4.27	37.00	45.47	54.47	11.80	14.37	14.65	29.80	34.60	38.29	11.50	15.65	19.72	0.45	0.71	0.95
SE(d)±	2.21	1.30	2.45	0.06	0.1	0.07	2.34	1.74	1.83	0.87	0.62	0.71	1.18	0.83	1.85	0.78	1.45	0.78	0.40	0.58	0.75
C.D. (5%)	4.52	2.66	5.02	0.12	0.21	0.15	4.79	3.55	3.74	1.79	1.27	1.46	3.69	1.69	3.78	1.60	2.96	1.59	0.04	0.06	0.04
CV (%)	7.01	3.49	5.57	4.97	4.97	1.90	6.56	4.09	3.54	8.39	4.66	7.98	6.89	2.52	4.93	6.74	8.91	4.02	0.08	0.12	0.09

Fig. 1: Effect of borax and ammonium molybdate on growth and yield of cauliflower

al. (2015) observed the maximum TSS (9.02^0 Brix) and ascorbic acid (51.52 mg/100) content of broccoli heads under application of 18 kg borax /ha and 1.5 kg ammonium molybdate/ha. Nie *et al.* (2008) reported that molybdenum application significantly increases chlorophyll content, ascorbic acid, soluble sugar, and soluble protein in Chinese cabbage.

The treatment T_6 (borax @ 20 kg/ha and ammonium molybdate @ 2 kg/ha) recorded the maximum curd yield of 258.67 q/ha and it also recorded the highest net returns of ₹ 1,51,715 and B:C ratio of 3.58, followed by (Table 2) lowest curd yield and net income was found in T_{10} (control) ie, 150.32 q/ha and ₹ 74,740.

CONCLUSION

The yield of cauliflower significantly increased due to combined application of boron and molybdenum as compared to individual application of either boron or molybdenum. The quality of cauliflower in terms of protein, vitamin-C, TSS, was found to be significantly superior with combined application of boron and molybdenum. Among all the treatments, borax @ 20 kg/ha + 2 kg/ha ammonium molybdate was to be best as it improved growth, yield and quality in Bundelkhand region (Jhansi). The application of borax @ 20 kg/ha + 2 kg/ha ammonium molybdate is most remunerative as it expressed the maximum income with a highest B:C ratio of 3.58.

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Table 2: Effect of borax and ammonium molybdate on yield and quality traits of cauliflower

Treatment	Days to curd initiation from transplanting	Days to curd maturity from initiation	Curd diameter (cm)	Fresh weight of curd (kg)	Yield per plot (kg/plot)	Yield per hectare (q/ha)	Grading of curd (%)			Chlorophyll content (mg/100g)	TSS (°Brix)	Protein content (%)	Ascorbic acid (mg/100g)	Dry matter content (%)	Net income	B:C ratio
							Grade A	Grade B	Grade C							
T_1 (borax @10 kg/ha+ RDF)	47.67	17.67	14.75	0.78	12.01	189.22	46.74	33.18	18.10	71.02	9.9	16.37	56.29	17.48	102504	2.60
T_2 (borax @ 10 kg/ha+ A.M.1 kg/ha + RDF)	43.67	15.67	14.39	0.65	13.01	205.09	48.14	35.15	15.38	67.48	9	14.91	61.30	19.3	112250.5	2.70
T_3 (borax @ 10 kg/ha + A.M. 2 kg/ha + RDF)	44.00	17.33	15.58	0.74	12.24	192.90	47.58	33.63	18.34	67.29	7.03	17.19	72.03	24.19	102908	2.46
T_4 (borax @ 20 kg/ha)	45.00	15.67	15.50	0.86	13.50	212.75	48.73	34.79	17.61	65.78	8.2	16.94	60.27	17.57	118453.5	2.88
T_5 (borax @ 20 kg/ha + A.M.1 kg/ha + RDF)	44.33	15.67	18.89	0.96	14.46	228.00	49.73	35.28	15.13	66.97	10.13	17.22	66.90	15.56	130411	3.21
T_6 (borax @ 20 kg/ha + A.M. 2 kg/ha + RDF)	42.00	13.67	20.88	1.17	16.41	258.67	52.17	36.13	12.95	71.22	10	18.12	85.60	26.11	151715	3.58
T_7 (A.M. @ 1 kg/ha)	45.00	16.00	16.07	0.82	12.36	194.74	48.69	33.19	18.80	71.45	9.1	15.24	59.56	15.3	105666	2.61
T_8 (A.M. @ 2 kg/ha + RDF)	44.00	17.00	15.50	0.64	11.93	188.12	50.08	34.61	18.58	84.43	9.63	14.26	71.33	24.04	99843	2.42
T_9 (RDF)	47.33	18.33	14.53	0.50	10.36	163.19	45.54	32.84	20.68	62.18	8.43	13.39	65.98	15.41	83501.5	2.14
T_{10} (control)	48.67	19.33	11.32	0.41	9.59	150.32	44.10	32.37	21.58	61.74	6.65	10.55	46.22	13.54	74740	1.90
SE(d)±	0.70	0.39	0.88	0.09	0.35	5.51	0.81	0.38	0.42	1.02	0.1	0.35	0.70	0.81		
C.D. @ 5%	1.42	0.79	1.80	0.19	0.71	11.27	1.66	0.79	0.86	2.04	0.2	0.71	1.42	1.65		
Coefficient of variation (%)	1.89%	2.86%	6.86	14.94	3.38	3.40	2.07	1.38	2.91	3.62	1.33	2.76	1.32	5.26		

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Current Horticulture 14(3): 3-15, July–September 2026
DOI: 10.5958/2455-7560.2026.00046.4
Received: 2 August 2026; Revised: 4 September 2024: Accepted: 4 September 2024

New Variety

New Nerium (*Nerium oleander*) varieties

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Nerium (*Nerium oleander* L.) is an evergreen ornamental flowering shrub, belongs to the family Apocynaceae. Commonly recognized as the dogbane family,it includes about 424 genera distributed in tropical and subtropical regions (Endress and Bruyns, 2000). Nerium is distributed in the Mediterranean region and subtropical Asia, is indigenous to India. The estimated area of Nerium cultivation is over 2,300 ha, highest area being in Tamil Nadu, Karnataka, Andhra Pradesh, Telangana and Kerala. It is a major traditional loose flower crop grown extensively for religious offerings, garland making etc. A systematic crop improvement programme was started to breed the novel varieties and hybrids of Nerium, during 2026. The University of Horticultural Sciences, Bagalkot, Karnataka, has released three Nerium varieties, Krishna Prabha Dishanth, Krishna Prabha Ratna and Krishna Prabha Ushashri for commercial cultivation. They are:

Krishna Prabha Dishanth: It is a clonal selection from germplasm maintained at the University of Horticultural Sciences, Bagalkot, Karnataka. The flowers are pink with single whorls with a bud length of 2.90cm and flower diameter of 4.30-4.50 cm. Its flowers are plucked 90-95 days after transplanting, producing 4.34 kg flowers/plant/year and peak flowering being from June to October.

Krishna Prabha Ratna: *Its* colour is red with single whorls. The bud length is 2.83 cm with flower diameter of 4.10-4.20 cm. It yields 3.08 kg flowers/plant/year, 85-90 days after transplanting, peak flowering season being from June to September.

Krishna Prabha Ushashri: Its flower colour is white with single whorls. The bud length is 2.76 cm with flower diameter of 4.30-4.50 cm. The flowers are ready for picking 95-100 days after transplanting, the yield being 3.86 kg flowers/plant/year.

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Continued on 3rd Cover

Continued from 2nd Cover

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Published by the Society for Horticultural Research and Development, SD-70, Shastri Nagar, Ghaziabad, and printed at M/s Chandu Press, 469, Patparganj Industrial Estate New Delhi, E-mail: chandupress@gmail.com

Editor: Dr Som Dutt

RNI No. UPENGO3865/24/1/2013-TC

ISSN (Print) : 2347-7377
ISSN (Online) : 2455-7560

Current Horticulture

(a journal dedicated for the advancement of Horticultural science)

Vol. 14 No. 2, July-September 2026

www.currenthorticulture.com