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, April-June 2026

www.currenthorticulture.com

(www.currenthorticulture.com)

Current Horticulture

(a journal dedicated for the advancement of Horticultural science)

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.

Corporate Office: SD-70, Shastri Nagar, Ghaziabad 201 002, Uttar Pradesh, India
Email: editorcurrenthort@gmail.com, somdutticar@gmail.com Phone: +91-9868815197

Continued on 3rd Cover

CURRENT HORTICULTURE

Vol 14, No. 2, April-June 2026

Contents

Current Horticulture **14(2): 3-15, April–June 2026**
DOI: 10.5958/2455-7560.2026.00015.4
Received: 14 May 2026; Accepted: 16 June 2026

Research Review Article

Breeding for yield and quality improvement in tomato (*Solanum lycopersicum*) using genetic variability and modern genomic tools

Samuel Boakye Yeboah [a], *Michael Kwabena Osei [ab], Hans Adu-Dapaah [a] and Justice Frederick Awuku [c]

[a] CSIR College of Science and Technology, Department of Plant Resources and Development, Kumasi Campus, Ghana CSIR-Crops Research Institute, Horticulture Division, P.O. BOX 3785, Kwadaso, Kumasi, Ghana CSIR-Savannah Agricultural Research Institute, P.O. Box 52, Nyankpala, Ghana

Abstract

Tomato (*Solanum lycopersicum* L.) is one of the most important horticultural crops in the world, but its production continually grapples with difficulty of improving yield without compromising fruit quality. To achieve, this balance requires breeders to make full use of the wide genetic diversity present in cultivated varieties, landraces, and wild relatives. This review synthesises current knowledge on global production trends, genetic basis of key agronomic and quality characteristics, and central role of diversity in sustaining breeding progress. Traditional breeding approaches, such as mass selection, pedigree breeding, backcrossing, and hybrid development have long supported tomato improvement, but their impact has grown significantly with the integration of molecular tools. Advances in QTL mapping, marker-assisted selection, genomic selection, multi-omics technologies, and CRISPR-based editing now make it easier to carefully study complex traits and adjust them with greater accuracy and control. These tools also help broaden the narrow genetic base created by domestication bottlenecks, allowing beneficial alleles from wild germplasm to be reintroduced into elite lines. Looking ahead, climate-smart breeding, high-throughput phenotyping, pangenomics, and farmer-participatory approaches offer promising pathways for developing cultivars that combine high yield, superior flavour and nutrition, and resilience to environmental stresses. Sustained exploitation of genetic variability therefore remains the foundation for meeting future productivity and quality demands in tomatoes.

Key words: QTL mapping, CRISPR/Cas9, Pangenome, Heterosis, *Genomics*, High-throughput phenotyping

Tomato (*Solanum lycopersicum* Linn., 2n = 2x = 24) is an annual, predominantly self-fertilising species that is widely recognized as one of the most important fruit vegetables worldwide (Waiba *et al.,* 2021). It represents about 16% of total vegetable production, generates an estimated market value of $58 billion, underscoring its immense economic importance (Villanueva Gutierrez, 2018). According to the *World Food and Agriculture – Statistical Yearbook 2024,* the production of tomato reached about 192 million tonnes globally, occupying nearly five million hectares worldwide (World Food and Agriculture, 2024). Tomato serves as an excellent source of essential vitamins and provitamins, including pro-vitamin A, folate, β-carotene and vitamin C, along with important minerals, such as potassium (Avdikos *et al.,* 2021; W. Liu *et al.,* 2022).

Despite its economic and nutritional prominence, tomato production faces serious challenges worldwide. Climate change has increased the frequency and severity of abiotic stresses, including drought, elevated temperatures, and irregular rainfall patterns, while biotic factors such as pests and diseases continue to constrain crop productivity (Sánchez-Bermúdez *et al.,* 2022). Additionally, post-harvest losses, which can exceed 30% in some regions, further constrain the profitability and sustainability of tomato cultivation. In Ghana, these issues are exacerbated by low productivity and a high dependence on imports. In Ghana, the estimated annual demand for tomatoes is approximately 1,048,000 metric tons, whereas local production is only about 500,000–510,000 metric tons, creating a significant supply deficit that compels reliance on imports (Business Ghana, 2024). To offset the domestic production shortfall, Ghana imports the majority of its fresh tomatoes from Burkina Faso, accounting for nearly 90 % of the nation's fresh tomato imports. Additionally imports substantial quantities of processed tomato products such as paste and concentrate from China, Italy, and other European countries. These imports are estimated at 78,000 tonnes of tomato paste annually, equivalent to 500,000 tonnes of fresh tomatoes (HortiDaily, 2024; RVO Netherlands, 2023). Tomato farming in Ghana is dominated by smallholder producers working on limited plots. In a recent survey, almost 90% of farmers operated on less than 2 ha (~5 acres), with many cultivating around 1–2 acres (~0.4–0.8 ha.) (Melomey *et al.,* 2022).

To meet these challenges, how can genetic variability be effectively harnessed to improve yield and quality of

Corresponding author : oranigh@gmail.com

tomato under diverse and changing environments? The extensive genetic diversity within *Solanum lycopersicum* and its wild relatives provides the foundation to develop improved varieties resilient to environmental stresses to achieve high yield with superior quality fruits (Bhandari *et al.,* 2017; Niehoff *et al.,* 2024). This review examines the role of genetic variability in tomato breeding for improving yield and fruit quality. It summarizes findings on key genetic parameters, including genotypic and phenotypic variation, heritability, genetic advance, correlation, and genotype × environment interactions, and their importance in selection. The review also emphasizes combining genomic tools with conventional breeding to accelerate the development of resilient, high-yielding, and nutritious tomato cultivars.

Tomato Production and Breeding

Global and regional production trends

Tomatoes are one of the most commonly grown and valuable vegetables worldwide. Global production has expanded dramatically over the past half-century – roughly sevenfold since 1960 – reaching the order of 186–192 million tonnes per year in the early 2020s (W. Li *et al.,* 2023). According to FAO data, world tomato output in 2020 was 186.8 million tonnes (worth about US $92.8 billion) (World Food and Agriculture, 2024). Major producers include China (by far the largest, 68–70 Mt), India (20–21 Mt), Turkey (13 Mt), the United States (12 Mt) and Egypt (6.2 Mt) (World Food and Agriculture, 2024). China alone accounts for one-third of the global output. Tomatoes rank among the top five crops worldwide by production volume with a substantial global market value (on the order of $100 billion annually), making tomatoes a key agricultural commodity (w. Li *et al.,* 2023).

Tomatoes have a major economic impact in developing regions. The fourth most valued food crop after rice, sugarcane and wheat grown in low and middle-income countries is the tomato (Schreinemachers *et al.,* 2022) . Every African country grows tomatoes, and its crop provides vital income and nutrition. Tomato and onion make the key ingredients in many traditional dishes eaten daily in West Africa (Awan *et al.,* 2012). In Africa, production is led by Egypt (with high yields and a large processing industry) and Nigeria (the largest producer by volume). (Schreinemachers *et al.,* 2022.).

Production (in tonnes) for major tomato-producing countries (China, India, USA, Brazil, Russia) showing long-term increases, especially the rapid growth in China since the 1990s.

Data source: Food and Agriculture Organization of the United Nations (FAO), accessed via *Our World in Data* (2025).

Tomatoes in Ghana

Ghana is classified as one of the major tomato-growing countries in West Africa. Recent FAO estimates put Ghana's production at 0.32–0.38 million tonnes annually (ca. 300–375 kt/year from 2009–2023) (Melomey *et al.,* 2022). This accounts for roughly 0.2% of the world output (Ghana ranked ~50th globally in 2023). Tomatoes are deeply important in the Ghanaian diet and economy: surveys report that tomato constitutes about 35% of a typical household's vegetable expenditure. It is estimated that some 90,000 smallholder farmers grow tomatoes and over 300,000 Ghanaians are linked to the tomato value chain nationwide (Awan *et al.,* 2012). However, Ghana relies heavily on imports of processed tomato paste to meet demand, reflecting gaps in domestic production and processing capacity.

Domestication history of tomato

Tomato has a well-documented domestication history. The wild progenitor is *S. pimpinellifolium*, a small-fruited species native to coastal Peru and Ecuador. Domestication commenced in the Andean region, South America and later ended in Mesoamerica (Mexico) (w. Li *et al.,* 2023). Intermediate forms include *S. lycopersicum* var. *cerasiforme* (a semi-domesticated cherry tomato found in the Andes). Over thousands of years, indigenous peoples selected larger and less-acidic fruits, leading to the ancestral cultivated tomato (Razifard *et al.,* 2020). This domestication "bottleneck" – followed by modern breeding – profoundly reduced genetic diversity. Studies show that cultivated tomatoes retain only a portion of the variation found in wild ancestors (Alatawi *et al.,* 2025; W. Li *et al.,* 2023). Indeed, traditional cultivars suffered a loss of diversity as varieties spread from the New World to Europe and Asia, and as intensive selection fixed preferred traits. For example, while wild

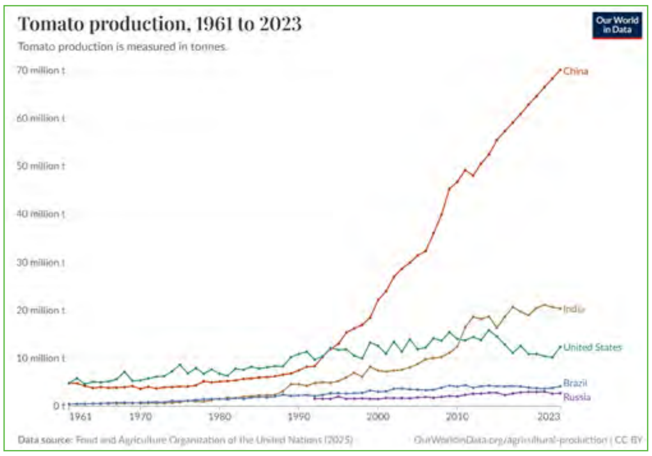


Fig. 1: Global tomato production trends from 1961 to 2023.

S. pimpinellifolium populations harbour rich variability in fruit colour, flavour and stress tolerance, much of that diversity was lost in early *S. lycopersicum* varieties (Li *et al.,* 2023).

Modern genomic analyses confirm this genetic narrowing. Cultivated tomato shows a clear bottleneck signal: many gene loci are fixed or low in diversity compared to wild relatives. This has implications for breeding: reduced allelic variation can limit the ability to improve traits. In response, breeders now recognize the need to tap wild and landrace germplasm. Wild relatives (like *S. pimpinellifolium*, *S. habrochaites*, *S. peruvianum* etc.) offer an "immense gene pool" of useful alleles (Alatawi *et al.,* 2025). For instance, disease-resistant genes such as *Pto* (against bacterial speck) and *Ph-3* (late blight resistant) were introduced into cultivated lines through the germplasms from the wild *S. pimpinellifolium (W. Li et al., 2023).*

Genetic Variability

Genetic variability refers to differences in DNA sequences and phenotypic variation in traits among conspecifics (Rasheed *et al.,* 2023). In tomato (*Solanum lycopersicum* L.), genetic variability is the cornerstone of programmes on breeding because it provides the raw material necessary to select desirable traits such as higher yield, improved fruit quality, tolerance to stress and resistance to disease(Rasheed *et al.,* 2023). Without sufficient variability, breeding progress becomes severely limited, as the scope for introducing beneficial traits is constrained (Jorgensen, 2012).

Sources of genetic variation

Genetic variation in tomato arises from multiple sources(FAO, 2019). Natural populations of wild species such as *S. pimpinellifolium*, *S. peruvianum*, and *S. habrochaites* harbour extensive allelic diversity, particularly for traits related to abiotic stress tolerance, disease resistance, and fruit quality (Lin *et al.,* 2014). Landraces, which are locally adapted, traditional varieties maintained by farmers, contribute additional variability, often containing alleles nonexistent in modern cultivars (Blanca *et al.,* 2015; Lin *et al.,* 2014). In addition, induced mutations, created through chemical mutagens, radiation, or modern genome editing techniques expand the genetic base and allow breeders to introduce novel alleles for characteristic, such as the shape of fruit, colour, and ripening rate (Li *et al.,* 2018, 2019; Tiwari *et al.,* 2023). Collectively, these sources provide a diverse pool of alleles that can be harnessed for targeted breeding (Li *et al.,* 2018, 2019; Tiwari *et al.,* 2023).

Assessment of genetic diversity

Assessing the extent of genetic variation is essential for effective breeding (Temesgen and Temesgen, 2024) . Traditionally, morphological traits such as shape, size of fruit, colour, and anatomy of plant have been used to evaluate variability among genotypes (Kumar Kundu, 2021). While informative, conditions of the environment affect these traits and may not fully reflect underlying genetic differences (Bauchet and Causse, 2012). To complement phenotypic assessment, biochemical markers such as isozyme and protein polymorphisms have been employed, revealing additional hidden variation at the molecular level (El-Sitiny *et al.,* 2022).

In modern breeding, molecular markers have become indispensable (Yali, 2022). Simple Sequence Repeats (SSR), Single Nucleotide Polymorphisms (SNPs), and Amplified Fragment Length Polymorphisms (AFLPs) enable precise genotyping, allowing breeders to assess population structure, track inheritance of target alleles, and perform marker-assisted selection (Chen *et al.,* 2025; W. Xu *et al.,* 2024; Yongsuwan *et al.,* 2024).

Traits Influencing Yield

Tomato yield is a complex trait influenced by multiple component characteristics that altogether influence the overall productivity of a genotype (Tsutsumi-Morita *et al.,* 2021). Yield is not a single attribute but rather a function of several interrelated factors, including fruit number per plant, fruit size, flowering behaviour, plant architecture, and resource-use efficiency.

Yield component traits

Fruit number is a major contributor to tomato yield and is influenced by flower production, pollination success, hormonal balance, environmental conditions, and plant's capacity to sustain fruit development (Azzi

Fig. 2: Genetic variability in tomato fruit: a variety of shapes (round, elongated, lobed), sizes (from cherry to beefsteak), and colours.

et al., 2015; Dinesh *et al.,* 2025). Fruit size contributes significantly to total yield, especially in market-driven production systems where uniform and large fruits are preferred. Fruit size is regulated by genes controlling cell division and expansion, such as FW2.2, FW3.2, and FW11.3, which have been linked to specific quantitative trait loci (QTLs) affecting fruit weight (Roohanitaziani *et al.,* 2020).

Heterosis and hybrid breeding

Hybrid breeding exploiting heterosis has been instrumental in increasing tomato productivity. Crosses between genetically diverse parents often produce F_1 hybrids with superior yield, uniformity, and stress resilience compared to either parent (Felföldi *et al.,* 2021; Z. Liu *et al.,* 2021). Hybrids are particularly needed for commercial fresh-market and processing tomatoes, where consistency in size, shape, and production duration is critical.

Trade-offs Between Yield and Stress Adaptability

While selection for high yield has historically driven productivity gains, trade-offs exist. Genotypes optimized for maximum yield under ideal conditions may be less adaptable to stress environments such as drought, heat, salinity, or pathogen pressure (Cirillo *et al.,* 2025; Graci and Barone, 2023; Meza *et al.,* 2020). Breeders must balance yield stability with adaptability, ensuring varieties perform consistently across environments while maintaining high fruit quality Modern breeding strategies integrate stress-tolerant alleles from wild relatives and landraces to mitigate these trade-offs, leveraging genomic selection and high-throughput phenotyping to identify resilient genotypes. Such varieties perform consistently across environments while maintaining high fruit quality (Tyagi *et al.,* 2024). Yield in tomato is a multi-component, quantitatively controlled trait shaped by genetics, physiology, and environment. Breeding programmes that integrate knowledge of component traits, polygenic control, QTLs, and heterosis, while accounting for trade-offs under stress, are key to sustaining and improving tomato productivity globally.

Genetic Basis of Fruit Quality Traits

Fruit quality in tomato is a multidimensional trait encompassing physical, nutritional, and sensory features that determine acceptance by consumers, market value, and nutritional benefits (Zhang *et al.,* 2023). Physical quality attributes include shape, fruit size, colour, and firmness, while nutritional quality encompasses lycopene content, vitamin C, sugars, and organic acids. Sensory quality is evaluated through flavour, aroma, and texture, which together influence the overall eating experience (Zhang *et al.,* 2023). The genetic control of these traits is complex, often polygenic, and tightly intertwined with biochemical pathways and environmental influences, making their improvement a central challenge in tomato breeding (Emmanuel Umeohia and Adekunle Olapade, 2024; Zhang *et al.,* 2023).

Breeding Approaches for Yield and Quality Improvement

Traditional breeding methods

Traditional breeding methods remain foundational in tomato improvement, each with unique strengths and limitations. Mass selection involves choosing the best-performing plants based on phenotype and bulking their seeds, which is simple, low-cost, and preserves existing cultivar traits, but improvement is slow and incremental (Abewoy Fentik, 2017; Sharma *et al.,* 2019). Pedigree breeding advances progeny through successive generations by selecting superior individuals from defined crosses, allowing trait combination and ancestry tracking; it accelerates cultivar development but is labour-intensive and may reduce genetic diversity over time (Abewoy Fentik, 2017; Sharma *et al.,* 2019). Backcross breeding transfers specific traits from donor lines into elite cultivars, precise for single-gene traits like disease resistance, though linkage drag can prolong programmes and introduce unwanted alleles (Chitwood-Brown *et al.,* 2021; Sharma *et al.,* 2019; Tripodi *et al.,* 2020). Finally, hybrid breeding exploits heterosis and uniformity, improving stability of yield and quality of fruits; however, heterosis in tomato is modest, and developing hybrid varieties requires extensive selfing, selection, and controlled crosses, making the process more laborious and costly (Z. Liu *et al.,* 2021; Soresa *et al.,* 2020) These traditional approaches complement each other, with choice depending on breeding objectives, available resources, and trait of interest.

Modern breeding methods

Modern breeding methods have significantly accelerated tomato improvement by enabling precise, rapid, and genome-informed selection (Cappetta *et al.,* 2020). Marker-assisted selection (MAS) uses DNA markers linked to target genes or QTL to identify desirable seedlings early, reducing phenotyping time and improving accuracy (Collard and Mackill, 2008). QTL mapping and genome-wide association studies (GWAS) have mapped numerous loci controlling yield, fruit size, soluble solids, colour and quality traits in biparental populations and diverse tomato panels, providing breeders with genomic

Table 1: Comparison of traditional tomato breeding methods, their strengths, limitations, and specific applications

Breeding Method	Key Features/Strengths	Limitations	Reference/Applications in Tomato
Mass selection	Low cost, preserves existing traits	Slow progress, relies on visible traits	Open-pollinated varieties (Abewoy Fentik, 2017; Sharma *et al.,* 2019)
Pedigree breeding	Combines multiple traits, tracks ancestry	Labor-intensive, may reduce diversity	Cultivar development programmes (Abewoy Fentik, 2017; Sharma *et al.,* 2019)
Backcross breeding	Precise introgression of specific traits	Linkage drag, time-consuming	Introgression of disease resistance genes from wild Solanum (Sharma *et al.,* 2019; Tripodi *et al.,* 2020; Chitwood-Brown *et al.,* 2021)
Hybrid breeding	Exploits heterosis, uniformity, yield stability	Modest heterosis, complex and costly parental line maintenance	Processing and F1 hybrids (z. Liu *et al.,* 2021; Soresa *et al.,* 2020)

targets for the improvement of traits (Causse *et al.,* 2004; Tripodi *et al.,* 2020). Genomic selection (GS) also improves the breeding pipeline by using genome-wide markers to predict breeding values, allowing early selection for traits that are highly polygenic such as yield and fruit quality, and thus accelerating genetic gain (Cappetta *et al.,* 2020). Genetic engineering and genome editing tools, including CRISPR/Cas, offer precise modification of genes controlling ripening, disease resistance, shelf life, and nutrition (Tiwari *et al.,* 2023). These methods bypass linkage drag and enable phenotypes unattainable through classical breeding, although regulatory and consumer acceptance issues remain (Abewoy Fentik, 2017; Vu *et al.,* 2020). Together, modern breeding methods provide high-resolution genomic insight and selection power, forming the core of contemporary tomato improvement programmes.

Integrating conventional and modern breeding

Modern tomato breeding increasingly merges classical and advanced methods to accelerate genetic gain. Instead of using each approach in isolation, breeders now stack technologies in tandem. For example, major disease and quality genes discovered by QTL mapping can be immediately fixed in elite lines by MAS, while genomic selection optimises polygenic traits. Indeed, Cappetta et al. (2020) emphasize that GS can be incorporated "in elite line selection, and descendant and backcross schemes" to boost gain. In practice, one might introgress a useful allele by MAS or CRISPR, then use GS on the segregating population to rapidly capture background improvements.

The CRISPR/Cas is the latest tool in this integrated toolbox. Alleles lost during domestication (for flavour nutrition, stress resistance) have traditionally been reintroduced by lengthy backcrossing with wild relatives. New genome-editing strategies, however, can "accelerate allele introgression" or even perform genome-wide gene stacking in one generation. For instance, the concept of de novo domestication exploits CRISPR to create "ideal" forms of wild tomato that carry multiple domesticated traits at once (Fernie and Yan, 2019). The edited plants can then enter conventional breeding programmes already far along, effectively leaping generations. This integration of precision editing with normal crosses could cut years off breeding time.

Role of Genetic Variability in Breeding Success

Genetic variability is the cornerstone of plant breeding programmes that have been a success (Temesgen and Temesgen, 2024).

Exploiting wild relatives for trait improvement

Wild relatives of cultivated tomatoes are invaluable sources of genetic diversity. Species such as *S.*

Table 2: Comparison of modern tomato breeding methods, their strengths, limitations, and specific applications

Modern Breeding Method	Key Features/Strengths	Limitations	Applications/References in Tomato
Marker-Assisted Selection (MAS)	Early DNA-based selection; speeds introgression; high accuracy	Requires reliable markers; limited for highly polygenic traits	Introgression of quality and resistance genes (Collard & Mackill, 2008; Lecomte *et al.,* 2004; Vu *et al.,* 2020)
QTL Mapping	Identifies genomic regions controlling traits	Low resolution; limited to biparental variation	*S. pennellii* ILs mapping fruit traits (Causse *et al.,* 2004)
GWAS	High-resolution mapping using natural diversity	Requires large diversity panels; susceptible to false positives	Loci for fruit size, shape, colour soluble solids (Tripodi *et al.,* 2021)
Genomic Selection (GS)	Predicts breeding value using genome-wide markers; ideal for polygenic traits	Requires large training populations and computational models	Enhanced prediction for yield and quality (Cappetta *et al.,* 2020)
Genetic Engineering & CRISPR	Precise gene modification; bypasses linkage drag; introduces novel traits	Regulatory restrictions; public acceptance issues	Flavr Savr tomato, virus resistance, shelf-life modification (Abewoy Fentik, 2017; Vu *et al.,* 2020)

pimpinellifolium, *S. habrochaites*, and *S. pennellii* harbour alleles for traits largely absent or diminished in modern cultivars due to the genetic bottleneck imposed by domestication(Mata-Nicolás *et al.,* 2020). These alleles have without fail been introgressed into elite cultivars to enhance both disease resistance and the quality of fruits (Barrantes *et al.,* 2016; Celik *et al.,* 2017).

Genetic diversity, adaptability, and sustainability

Broad genetic variability underpins both short-term breeding success and long-term sustainability. Diverse germplasm provides alleles that allow breeders to respond to emerging biotic stresses (new pathogens or pest strains) and abiotic stresses (drought, salinity, heat). For instance, the introgression of multiple disease resistance genes from wild relatives not only improved current cultivars but also provided genetic "insurance" against pathogen evolution (A. Kaur and Sangha, 2023). This dynamic adaptability is critical as climate change introduces novel stress patterns and expands cultivation into marginal environments (Causse *et al.,* 2013; Kapazoglou *et al.,* 2023; Rose *et al.,* 2025).

The importance of wild and exotic germplasm is further highlighted in long-term sustainability of plant breeding (Kapazoglou *et al.,* 2023). Landraces and wild relatives act as reservoirs for traits that may not be immediately needed but become critical under changing environments or pathogen pressures. Programmes that systematically conserve, characterize, and utilize these resources—such as the Tomato Genetics Resource Center (TGRC) and IL collections—illustrate how broad genetic variability is a practical necessity for sustained genetic gain (Bai ans Lindhout, 2007; Hussain *et al.,* 2025).

The evidence is clear: genetic variability is fundamental to breeding success in tomato. Wild relatives and landraces provide alleles for disease resistance, stress tolerance, and fruit quality that are largely absent in modern cultivars (Kapazoglou *et al.,* 2023).

Challenges and Future Prospects in Tomato Breeding

Tomato improvement has achieved remarkable progress over the last century, yet the crop continues to face complex genetic, environmental, and market-driven pressures that constrain breeding efficiency. Many of these challenges stem from long-term domestication, modern production demands, and the increasing unpredictability of climate stressors. Addressing them requires not only access to broad genetic diversity but also the integration of cutting-edge technologies and innovative breeding approaches that align yield, quality, and resilience goals (Du *et al.,* 2025).

Ongoing challenges

Genetic erosion and narrow breeding pools

One of the most persistent challenges is *genetic erosion*—the loss of allelic diversity in cultivated tomato due to domestication, modern selection, and widespread commercialization of uniform hybrids. The process of domestication and repeated selective breeding has greatly reduced genetic diversity compared to wild relatives, leaving breeders with only a limited number of alleles for complex traits like flavour, hardiness, and nutrient content (Lin *et al.,* 2014).

Limited germplasm exchange

Although wild relatives contain valuable alleles, *access and exchange of germplasm* remain constrained by regulatory barriers, intellectual property rights, and insufficient international collaborations. Many breeding programmes rely on a small subset of accessible lines, while vast collections maintained in gene banks remain underutilized due to poor characterization or lack of molecular data (Ebert *et al.,* 2023; Nguyen & Norton, 2020).

Consumer-driven uniformity

Modern supply chains and consumer markets demand *uniform fruit shape, colour ripening behaviour, and shelf life*. These expectations lead breeders to prioritize appearance and firmness over broader variation in flavour and nutritional composition. Over time, this has reinforced selection for a narrow set of phenotypes that meet commercial needs, often at the expense of flavour aroma, and micronutrient diversity (G. Kaur *et al.,* 2023; Nie *et al.,* 2024; Tieman *et al.,* 2017).

Climate change and stress interactions

Rising temperatures, erratic rainfall, high salinity, and emerging pest complexes pose new challenges for tomato production. Many elite cultivars lack broad-based tolerance, and stress interactions such as heat combined with drought are rarely addressed in traditional breeding (Bai *et al.,* 2018; Fernández-Crespo *et al.,* 2022; Roșca *et al.,* 2023).

Technological opportunities to overcome these challenges

Despite the constraints, recent advances in genomics and phenotyping offer unprecedented opportunities to expand usable variability and accelerate genetic gain.

Pangenomics and structural variant discovery

The tomato *pangenome is* constructed from multiple cultivated and wild accessions which capture genomic regions absent from the reference genome. Pangenomic studies reveal structural variations, presence–absence variants, and hidden allelic diversity that were previously undetectable. These new insights allow breeders to target novel genes affecting quality of fruit, resistance to disease, and abiotic stress tolerance (Gao *et al.,* 2019).

High-throughput phenotyping (HTP)

High-throughput phenotyping (HTP) has rapidly evolved thanks to advances in imaging systems, drones, hyperspectral sensors, and automated greenhouse platforms (Xu & Li, 2022). These technologies allow breeders to precisely measure complex, traits such as canopy temperature (a proxy for water or heat stress), biomass accumulation, plant architecture, and even biochemical features of fruit across different environments and time points. By integrating computer vision, machine learning, and frequent imagery, HTP dramatically reduces the labour and cost associated with traditional, manual measurements (Aono *et al.,* 2021; R. Xu and Li, 2022).

Multi-omics integration

Modern breeding increasingly relies on multi-omics integration which combines genomics, transcriptomics, metabolomics, and proteomics and these help to unravel the complex biochemical networks that underlie traits like flavour, lycopene synthesis, sugar–acid balance, and stress responses(Pascual *et al.,* 2025). For instance, systems biology studies in tomato using transcriptomic, proteomic, and metabolomic layers have revealed how key ripening regulators such as NOR and RIN coordinate metabolic shifts in sugars, organic acids, and cell-wall compounds (Osorio *et al.,* 2011). Multi-omics approaches have also shown how cold storage reprograms secondary metabolism: low-temperature treatment dramatically alters flavonoid and phenylpropanoid metabolites, and this correlates with the structural genes expression and factors of trascription like *SlCHS* as well as *MYB70 (*Liu *et al.,* 2023*).* In stress studies, integration of transcriptome and metabolome data under combined abiotic stresses uncovered regulatory hubs involving amino-acid, sugar, and hormone pathways, highlighting candidate genes and metabolites that might be key to climate resilience breeding (Pascual *et al.,* 2025).

Bioinformatics and AI-driven breeding

Machine learning and AI algorithms are revolutionising how breeders interpret complex data and make breeding decisions. These models can predict genotype performance under different environmental conditions, forecast how alleles will interact, and simulate how specific crossing designs will perform. AI-driven platforms help breeders identify favourable haplotypes, optimise parent selection, and prioritise crosses, especially when working with highly polygenic traits (e.g. yield, flavour, stress resilience). By integrating genomic, phenotypic, and environmental datasets, these tools accelerate decision-making and increase breeding program efficiency ultimately decreasing the time and cost needed to deliver improved tomato varieties (Farooq *et al.,* 2024; Gerakari *et al.,* 2025).

Strengthening pre-breeding and participatory approaches

Pre-breeding to unlock wild diversity

Pre-breeding is a crucial step in modern tomato breeding, allowing the transfer of valuable alleles from wild relatives — such as *S. pennellii*, *S. habrochaites*, and *S. pimpinellifolium* — into intermediate lines while minimizing linkage drag (A. Kaur and Sangha, 2023). These intermediate lines act as a bridge, expanding the usable genetic base and making wild alleles (Lecomte *et al.,* 2004)more accessible for integration into elite cultivars. Through pre-breeding, researchers have successfully identified QTLs associated with important traits, such as soluble solids content, disease resistance (e.g. resistance to bacterial speck, nematodes, and viruses), and abiotic stress tolerance, which can then be directly exploited in commercial breeding programmes. This approach not only widens the genetic diversity available for selection but also speeds the development of high-performing, resilient, and quality-focused tomato varieties (Thapa *et al.,* 2015; Zsögön *et al.,* 2018) .

Participatory breeding

Participatory breeding is a deeply empowering process that brings farmers, processors, consumers, and scientists into the same conversation, not just as recipients of new varieties, but as active decision-makers. In smallholder-dominated regions in Africa and Asia, this matters a great deal: farmers know their land, their climate, and their market conditions intimately, and when they help select and breed crops, the resulting varieties are more likely to combine productivity with resilience and the traits people truly value (such as taste, cooking quality, or post-harvest features). By enriching the breeding environment with local voices, participatory breeding helps develop cultivars that suit real-life conditions rather than ideal research station plots, accelerating adoption, boosting biodiversity, and building trust between researchers and communities. Studies in Ethiopia, for example, show that involving farmers in bean breeding leads to selection based on 40+ criteria, from drought tolerance to cooking colour and results in varieties farmers are more likely to grow and maintain (Al-Tawaha *et al.,* 2005). Similarly, participatory programmes in maize across Sub-Saharan Africa have shown that farmer-preferred traits often diverge from breeder-only priorities (Worku *et al.,* 2020). This inclusive approach also strengthens social capital, as farmers gain new skills and take ownership of seed systems, and it contributes to food sovereignty by preserving and enhancing locally adapted genetic diversity (Greenberg, 2018).

Climate-smart breeding

Climate-smart breeding strategies intentionally build resilience into new varieties so they can withstand rising temperatures, erratic water availability, and soil salinity while still producing high-quality fruit. For instance, breeders are selecting for heat-tolerant flowering and stable fruit set under stress using Quantitative Trait Loci (QTL) associated with yield and soluble solids under heat stress (Cappetta *et al.,* 2021; Elazazi *et al.,* 2024). At the same time, they pyramid multiple stress-tolerance genes *via* marker-assisted selection (MAS) or genomic selection, which leverages genome-wide markers to predict performance under combined stress environments (Cappetta *et al.,* 2021). Additionally, grafting onto vigorous rootstocks derived from wild relatives like *Solanum pimpinellifolium* and *S. habrochaites* is increasingly used to boost tolerance to salinity and maintain nutrient balance under salt stress (Aydin, 2024). Together, these strategies align breeding with future climate scenarios, ensuring new cultivars remain both productive and resilient, and helping farmers sustain yields even as growing conditions change.

Vision for Future: Precision and Resilient Tomato Improvement

The future of tomato breeding lies in combining broad genetic diversity with precision tools that allow breeders to sculpt phenotypes with unprecedented accuracy (Yali, 2022). Pangenomic resources, multi-omics insights, CRISPR-mediated editing, and genomic prediction models will enable targeted improvement of traits previously considered too complex or polygenic(Cappetta *et al.,* 2021; Fernie & Aharoni, 2019; Gao *et al.,* 2019; Pascual *et al.,* 2025; Rönspies *et al.,* 2021; Yeon *et al.,* 2024; Zhou *et al.,* 2022).

A resilient future tomato cultivar will be one that:

- draws from the broadest possible genetic base
- withstands multiple stress combinations
- satisfies consumer demand for flavour, nutrition, and shelf life
- performs predictably across diverse environments
- is developed through data-driven, farmer-inclusive breeding
- leverages precision breeding tools to accelerate genetic gain

CONCLUSION

Sustainable enhancement of tomato yield and fruit quality ultimately depends on the continuous exploration, conservation, and strategic use of genetic variability. The collective evidence demonstrates that broadening the genetic base through wild relatives, landraces, pre-breeding, and modern genomic tools is essential for unlocking new alleles that support resilience, nutritional improvement, and long-term productivity. Traditional breeding strategies continue to provide a reliable foundation, but their power increases substantially when integrated with advanced genomic, transcriptomic, metabolomic, and genome-editing technologies. These tools not only accelerate selection but also enable precise manipulation of complex traits previously limited by narrow diversity and long breeding cycles. Moving forward, a holistic breeding paradigm that merges classical knowledge with cutting-edge biotechnology, data-driven prediction, and climate-smart strategies will be critical. Such integration will ensure the development of tomato cultivars that meet global expectations for yield, flavour, nutrition, and environmental adaptability. Maintaining and expanding genetic diversity is therefore not optional, it is the defining requirement for future tomato improvement and for securing both productivity and nutritional security in an increasingly unstable climate.

REFERENCES

Abewoy Fentik, D. (2017). Review on Genetics and Breeding of Tomato (Lycopersicon esculentum Mill). *Advances in Crop Science and Technology* **5**(5). https://doi.org/10.4172/2329-8863.1000306

Alatawi, I., Xiong, H., Alkabkabi, H., Chiwina, K., Luo, Q., Ling, K. S., Qu, Y., Du, R., & Shi, A. (2025). Genetic Diversity and Population Structure of Tomato (Solanum lycopersicum) from the USDA-GRIN Germplasm Collection. *Agronomy* **15**(1). https://doi.org/10.3390/agronomy15010022

Al-Tawaha, A.-R. M., Assefa, T., Abebe, G., Fininsa, C., & Tesso, B. (2005). Participatory Bean Breeding with Women and Small Holder Farmers in Eastern Ethiopia. *World Journal of Agricultural Sciences* **1**(1): 28–35.

Aono, Y., Asikin, Y., Wang, N., Tieman, D., Klee, H., & Kusano, M. (2021). High-Throughput Chlorophyll and Carotenoid Profiling Reveals Positive Associations with Sugar and Apocarotenoid Volatile Content in Fruits of Tomato Varieties in Modern and Wild Accessions. *Metabolites,*

11(6): 398. https://doi.org/10.3390/metabo11060398

Avdikos, I. D., Tagiakas, R., Tsouvaltzis, P., Mylonas, I., Xynias, I. N., & Mavromatis, A. G. (2021). Comparative evaluation of tomato hybrids and inbred lines for fruit quality traits. *Agronomy* **11**(3). https://doi.org/10.3390/agronomy11030609

Awan, M. S., Hussain, A., Abbas, T., & Karim, R. (2012). Assessment of production practices of small scale farm holders of tomato in Bagrote Valley, CKNP region of Gilgit-Baltistan, Pakistan.

Aydin, A. (2024). Effects of grafting with wild tomato (*Solanum pimpinellifolium* and *Solanum habrochaites*) rootstocks on growth and leaf mineral accumulation in salt stress. In *Horticulture Environment and Biotechnology* **65**(5): 785–801. Springer. https://doi.org/10.1007/s13580-024-00607-5

Azzi, L., Deluche, C., Gévaudant, F., Frangne, N., Delmas, F., Hernould, M., & Chevalier, C. (2015). Fruit growth-related genes in tomato. In *Journal of Experimental Botany* **66**(4):1075-86. Oxford University Press. https://doi.org/10.1093/jxb/eru527

Bai, Y., & Lindhout, P. (2007). Domestication and breeding of tomatoes: What have we gained and what can we gain in the future? In *Annals of Botany* **100** (5):1085–1094. https://doi.org/10.1093/aob/mcm150

Barrantes, W., López-Casado, G., García-Martínez, S., Alonso, A., Rubio, F., Ruiz, J. J., Fernández-Muñoz, R., Granell, A., & Monforte, A. J. (2016). Exploring new alleles involved in tomato fruit quality in an introgression line library of solanum pimpinellifolium. *Frontiers in Plant Science*, *7*(AUG2016). https://doi.org/10.3389/fpls.2016.01172

Bauchet, G., & Causse, M. (2012). *8 Genetic Diversity in Tomato (Solanum lycopersicum) and Its Wild Relatives*. www.intechopen.comBhandari, H. R., Srivastava, K., & Reddy, G. E. (2017). Ge

netic Variability, Heritability and Genetic Advance for Yield Traits in Tomato (Solanum lycopersicum L.). *International Journal of Current Microbiology and Applied Sciences* **6**(7): 4131–38. https://doi.org/10.20546/ijcmas.2017.607.428

Blanca, J., Montero-Pau, J., Sauvage, C., Bauchet, G., Illa, E., Díez, M. J., Francis, D., Causse, M., van der Knaap, E., & Cañizares, J. (2015). Genomic variation in tomato, from wild ancestors to contemporary breeding accessions. *BMC Genomics* **16**(1). https://doi.org/10.1186/s12864-015-1444-1

BusinessGhana. (2024). *Berekum West tomato growers introduced to new varieties for improved production*. BusinessGhana. https://www.businessghana.com/site/news/Business/292039/Berekum-West-tomato-growers-introduced-to-new-varieties-for-improved-production

Cappetta, E., Andolfo, G., Di Matteo, A., Barone, A., Frusciante, L., & Ercolano, M. R. (2020). Accelerating tomato breeding by exploiting genomic selection approaches. *Plants* **9**(9): 1–14. https://doi.org/10.3390/plants 9091236

Cappetta, E., Andolfo, G., Guadagno, A., Di Matteo, A., Barone, A., Frusciante, L., & Ercolano, M. R. (2021). Tomato genomic prediction for good performance under high-temperature and identification of loci involved in thermotolerance response. *Horticulture Research* **8**(1). https://doi.org/10.1038/s41438-021-00647-3

Causse, M., Desplat, N., Pascual, L., Le Paslier, M.-C., Sauvage, C., Bauchet, G., Bérard, A., Bounon, R., Tchoumakov, M., Brunel, D., & Bouchet, J.-P. (2013). Whole genome resequencing in tomato reveals variation associated with introgression and breeding events. http://www.biomedcentral.com/1471-2164/14/791

Causse, M., Duffe, P., Gomez, M. C., Buret, M., Damidaux, R., Zamir, D., Gur, A., Chevalier, C., Lemaire-Chamley, M., & Rothan, C. (2004). A genetic map of candidate genes and QTLs involved in tomato fruit size and composition. *Journal of Experimental Botany* **55**(403): 1671–1685. https://doi.org/10.1093/jxb/erh207

Celik, I., Gurbuz, N., Uncu, A. T., Frary, A., & Doganlar, S. (2017). Genome-wide SNP discovery and QTL mapping for fruit quality traits in inbred backcross lines (IBLs) of solanum pimpinellifolium using genotyping by sequencing. *BMC Genomics* **18**(1). https://doi.org/10.1186/s12864-016-3406-7

Chen, X., Liu, Y. Y., Zheng, F. S., Cheng, G. X., Guo, M., Li, J. S., & Wang, X. M. (2025). Construction of a core collection of tomato (Solanum lycopersicum) germplasm based on phenotypic traits and SNP markers. *Scientia Horticulturae* **339**. https://doi.org/10.1016/j.scienta.2024.113855

Chitwood-Brown, J., Vallad, G. E., Lee, T. G., & Hutton, S. F. (2021). Characterization and elimination of linkage-drag associated with Fusarium wilt race 3 resistance genes. *Theoretical and Applied Genetics* **134**(7): 2129–40. https://doi.org/10.1007/s00122-021-03810-5

Cirillo, V., Ruggiero, A., Caullireau, E., di Covella, F. S., Francesca, S., Grillo, S., Batelli, G., & Maggio, A. (2025). Isolating Water and Nitrogen Stress Tolerant Genotypes Among Tomato Landraces and Solanum pennellii Backcross Inbred Lines. *Journal of Plant Growth Regulation* **44**(5): 2367–2378. https://doi.org/10.1007/s00344-024-11552-z

Collard, B. C. Y., & Mackill, D. J. (2008). Marker-assisted selection: An approach for precision plant breeding in the twenty-first century. In *Philosophical Transactions of the Royal Society B: Biological Sciences* 363(1491):557–72. Royal Society. https://doi.org/10.1098/rstb.2007.2170

Dinesh, A., Prasanth, P., Lakshminarayana, D., Nagaraju, K., & Gouthami, P. (2025). Correlation studies on growth, flowering and yield attributes of cucumber (Cucumis sativus L.) cv. Malini under plant growth regulator treatments. *International Journal of*

Research in Agronomy **8**(12): 1314–1317. https://doi.org/10.33545/2618060x.2025.v8.i12r.4641

Du, M., Sun, C., Deng, L., Zhou, M., Li, J., Du, Y., Ye, Z., Huang, S., Li, T., Yu, J., Li, C. B., & Li, C. (2025). Molecular breeding of tomato: Advances and challenges. In *Journal of Integrative Plant Biology* **67**(3): 669–721. https://doi.org/10.1111/jipb.13879

Ebert, A. W., Engels, J. M. M., Schafleitner, R., Hintum, T. van, & Mwila, G. (2023). Critical Review of the Increasing Complexity of Access and Benefit-Sharing Policies of Genetic Resources for Genebank Curators and Plant Breeders–A Public and Private Sector Perspective. In *Plants* 12, (16). https://doi.org/10.3390/plants12162992

Elazazi, E., Ziems, L., Mahmood, T., Eltanger, N., Al-Qahtani, M., Shahsil, N., Al-Kuwari, A., Metwally, M. M., Trethowan, R., & Dong, C. (2024). Genotypic Selection Using Quantitative Trait Loci for Better Productivity under High Temperature Stress in Tomato (Solanum lycopersicum L.). *Horticulturae* **10**(8). https://doi.org/10.3390/horticulturae10080874

El-Sitiny, M. F. A., M. Omar, H., El-Shehawi, A. M., Elseehy, M. M., El-Tahan, A. M., El-Saadony, M. T., & Selem, G. S. (2022). Biochemical and molecular diagnosis of different tomato cultivars susceptible and resistant to Tuta absoluta (Meyrick) infestation: Biochemical and molecular diagnosis of different tomato cultivars susceptible and resistant to Tuta absoluta. *Saudi Journal of Biological Sciences* **29**(4): 2904–2910. https://doi.org/10.1016/j.sjbs.2022.01.024

Emmanuel Umeohia, U., & Adekunle Olapade, A. (2024). Quality Attributes, Physiology, and Postharvest Technologies of Tomatoes (Lycopersicum Esculentum) – A Review. *American Journal of Food Science and Technology* **12**(2): 42–64. https://doi.org/10.12691/ajfst-12-2-1

FAO. (2019). The state of the world's biodiversity for food and agriculture fao commission on genetic resources for food and agriculture assessments • 2019 .

Farooq, M. A., Gao, S., Hassan, M. A., Huang, Z., Rasheed, A., Hearne, S., Prasanna, B., Li, X., & Li, H. (2024). Artificial intelligence in plant breeding. *Trends in Genetics* **40**(10): 891–908. https://doi.org/https://doi.org/10.1016/j.tig.2024.07.001

Felföldi, Z., Ranga, F., Socaci, S. A., Farcas, A., Plazas, M., Sestras, A. F., Vodnar, D. C., Prohens, J., & Sestras, R. E. (2021). Physico-chemical, nutritional, and sensory evaluation of two new commercial tomato hybrids and their parental lines. *Plants* **10**(11). https://doi.org/10.3390/plants10112480

Fernie, A. R., & Aharoni, A. (2019). Pan-Genomic Illumination of Tomato Identifies Novel Gene–Trait Interactions. *Trends in Plant Science* **24**(10): 882–884. https://doi.org/10.1016/j.tplants.2019.08.001

Fernie, A. R., & Yan, J. (2019). De novo domestication: an alternative route toward new crops for the future. *Molecular Plant* **12**: 615–631. https://doi.org/10.1016/j.molp.2019.03.016

Gao, L., Gonda, I., Sun, H., Ma, Q., Bao, K., Tieman, D. M., Burzynski-Chang, E. A., Fish, T. L., Stromberg, K. A., Sacks, G. L., Thannhauser, T. W., Foolad, M. R., Diez, M. J., Blanca, J., Canizares, J., Xu, Y., van der Knaap, E., Huang, S., Klee, H. J., and Fei, Z. (2019). The tomato pan-genome uncovers new genes and a rare allele regulating fruit flavour. *Nature Genetics* **51**(6): 1044–1051. https://doi.org/10.1038/s41588-019-0410-2

Gerakari, M., Katsileros, A., Kleftogianni, K., Tani, E., Bebeli, P. J., & Papasotiropoulos, V. (2025). Breeding of Solanaceous Crops Using AI: Machine Learning and Deep Learning Approaches—A Critical Review. In *Agronomy* **15**(3). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/agronomy15030757

Graci, S., & Barone, A. (2023). Tomato plant response to heat stress: a focus on candidate genes for yield-related traits. In *Frontiers in Plant Science* **14**. Frontiers Media SA. https://doi.org/10.3389/fpls.2023.1245661

Greenberg, S. (2018). *A review of participatory plant breeding and lessons for African seed and food sovereignty movements (ACB report)*. www.acbio.org.za

HortiDaily. (2024). *Ghana tomato imports from Burkina Faso hit US$400 million annually*. HortiDaily. https://www.hortidaily.com/article/9470128/ghana-tomato-imports-from-burkina-faso-hit-us-400-mln-annually/

Hussain, E., Cheng, C. Y., Huang, I. M., Lin, C. Y., Gul, S., Noorka, I. R., Eybishitz, A., Kanchana-udomkan, C., van Zonneveld, M., & Lin, Y. P. (2025). Molecular screening of wild and cultivated tomato germplasm reveals potential materials for multi-locus disease resistance breeding. *Genetic Resources and Crop Evolution* **72**(7): 8619–8632.https://doi.org/10.1007/s10722-025-02457-1

Jorgensen, R. A. (2012). A vision for 21st century agricultural research. *Frontiers in Plant Science* ***3*** (JUL). https://doi.org/10.3389/fpls.2012.00157

Kapazoglou, A., Gerakari, M., Lazaridi, E., Kleftogianni, K., Sarri, E., Tani, E., & Bebeli, P. J. (2023). Crop Wild Relatives: A Valuable Source of Tolerance to Various Abiotic Stresses. In: *Plants* **12**(2). https://doi.org/10.3390/plants12020328

Kaur, A., & Sangha, M. K. (2023). Crop Wild Relatives (CWRs) a Genetic Pool for Crop Improvement: A Review. *Agricultural Reviews*, (Of). https://doi.org/10.18805/ag.r-2613

Kaur, G., Abugu, M., & Tieman, D. (2023). The dissection of tomato flavor: biochemistry, genetics, and omics. In *Frontiers in Plant Science* **14**. Frontiers Media S.A. https://doi.org/10.3389/fpls.2023.1144113

Kumar Kundu, P. (2021). Morphological characterization and genetic divergence in brinjal genotypes *(Solanum melongena L.)*.

Lecomte, L., Duffé, P., Buret, M., Servin, B., Hospital, F., & Causse, M. (2004). Marker-assisted introgression of five QTLs controlling fruit quality traits into three tomato lines revealed interactions between QTLs and genetic backgrounds. *TAG. Theoretical and Applied Genetics. Theoretische Und Angewandte Genetik* **109**(3): 658–668. https://doi.org/10.1007/s00122-004-1674-0

Li, R., Fu, D., Zhu, B., Luo, Y., & Zhu, H. (2018). CRISPR/Cas9-mediated mutagenesis of lncRNA1459 alters tomato fruit ripening. *Plant Journal* **94**(3): 513–524. https://doi.org/10.1111/tpj.13872

Li, R., Liu, C., Zhao, R., Wang, L., Chen, L., Yu, W., Zhang, S., Sheng, J., & Shen, L. (2019). CRISPR/Cas9-Mediated SlNPR1 mutagenesis reduces tomato plant drought tolerance. *BMC Plant Biology* **19**(1). https://doi.org/10.1186/s12870-018-1627-4

Li, W., Li, Y., Liang, Y., Ni, L., Huang, H., Wei, Y., Wang, M., Zhang, L., & Zhao, L. (2023). Generating Novel Tomato Germplasm Using the Ancestral Wild Relative of *Solanum pimpinellifolium*. *Horticulturae* **9**(1). https://doi.org/10.3390/horticulturae9010034

Lin, T., Zhu, G., Zhang, J., Xu, X., Yu, Q., Zheng, Z., Zhang, Z., Lun, Y., Li, S., Wang, X., Huang, Z., Li, J., Zhang, C., Wang, T., Zhang, Y., Wang, A., Zhang, Y., Lin, K., Li, C., ... Huang, S. (2014). Genomic analyses provide insights into the history of tomato breeding. *Nature Genetics* **46**(11): 1220–26. https://doi.org/10.1038/ng.3117

Liu, W., Liu, K., Chen, D., Zhang, Z., Li, B., El-Mogy, M. M., Tian, S., & Chen, T. (2022). Solanum lycopersicum, a Model Plant for the Studies in Developmental Biology, Stress Biology and Food Science. *Foods* **11**(16). https://doi.org/10.3390/foods11162402

Liu, Y., Tang, N., Lin, D., Deng, W., & Li, Z. (2023). Integration of multi-omics analyses highlights the secondary metabolism response of tomato fruit to low temperature storage. *Food Research International, 173*, 113316. https://doi.org/https://doi.org/10.1016/j.foodres.2023.113316

Liu, Z., Jiang, J., Ren, A., Xu, X., Zhang, H., Zhao, T., Jiang, X., Sun, Y., Li, J., & Yang, H. (2021). *Heterosis and Combining Ability Analysis of Fruit Yield, Early Maturity, and Quality in Tomato*. https://doi.org/10.3390/agronomy

Mata-Nicolás, E., Montero-Pau, J., Gimeno-Paez, E., Garcia-Carpintero, V., Ziarsolo, P., Menda, N., Mueller, L. A., Blanca, J., Cañizares, J., van der Knaap, E., & Díez, M. J. (2020). Exploiting the diversity of tomato: the development of a phenotypically and genetically detailed germplasm collection. *Horticulture Research* **7**(1). https://doi.org/10.1038/s41438-020-0291-7

Melomey, L. D., Ayenan, M. A. T., Marechera, G., Abu, P., Danquah, A., Tarus, D., & Danquah, E. Y. (2022). Pre and Post-Harvest Practices and Varietal Preferences of Tomato in Ghana. *Sustainability (Switzerland)* **14**(3). https://doi.org/10.3390/su14031436

Meza, S. L. R., Egea, I., Massaretto, I. L., Morales, B., Purgatto, E., Egea-Fernández, J. M., Bolarin, M. C., & Flores, F. B. (2020). Traditional Tomato Varieties Improve Fruit Quality Without Affecting Fruit Yield Under Moderate Salt Stress. *Frontiers in Plant Science* **11**. https://doi.org/10.3389/fpls.2020.587754

Nguyen, G. N., & Norton, S. L. (2020). Genebank phenomics: A strategic approach to enhance value and utilization of crop germplasm. *Plants* **9**(7): 1–27 https://doi.org/10.3390/plants9070817

Nie, H., Yang, X., Zheng, S., & Hou, L. (2024). Gene-Based Developments in Improving Quality of Tomato: Focus on Firmness, Shelf Life, and Pre- and Post-Harvest Stress Adaptations. *Horticulturae* **10** (6). https://doi.org/10.3390/horticulturae10060641

Niehoff, T. A. M., ten Napel, J., Bijma, P., Pook, T., Wientjes, Y. C. J., Hegedűs, B., & Calus, M. P. L. (2024). Improving selection decisions with mating information by accounting for Mendelian sampling variances looking two generations ahead. *Genetics Selection Evolution* **56**(1). https://doi.org/10.1186/s12711-024-00899-2

Osorio, S., Alba, R., Damasceno, C. M. B., Lopez-Casado, G., Lohse, M., Zanor, M. I., Tohge, T., Usadel, B., Rose, J. K. C., Fei, Z., Giovannoni, J. J., & Fernie, A. R. (2011). Systems biology of tomato fruit development: Combined transcript, protein, and metabolite analysis of tomato transcription factor (nor, rin) and ethylene receptor (Nr) mutants reveals novel regulatory interactions. *Plant Physiology* **157**(1): 405–425. https://doi.org/10.1104/pp.111.175463

Pascual, L. S., Serna, E., Ghani, A., Lyu, Z., Immadi, M. S., Joshi, T., Verma, M., Rambla, J. L., Gómez-Cadenas, A., Mittler, R., & Zandalinas, S. I. (2025). Multi-omics-based insights into tomato adaptation to multifactorial stress combination. *Plant Physiology* **199**(3). https://doi.org/10.1093/plphys/kiaf519

Rasheed, A., Ilyas, M., Khan, T. N., Mahmood, A., Riaz, U., Chattha, M. B., Al Kashgry, N. A. T., Binothman, N., Hassan, M. U., Wu, Z., & Qari, S. H. (2023). Study of genetic variability, heritability, and genetic advance for yield-related traits in tomato (*Solanum lycopersicon* MILL.). *Frontiers in Genetics* **13**. https://doi.org/10.3389/fgene.2022.1030309

Razifard, H., Ramos, A., Della Valle, A. L., Bodary, C., Goetz, E., Manser, E. J., Li, X., Zhang, L., Visa, S., Tieman, D., van der Knaap, E., & Caicedo, A. L. (2020). Genomic Evidence for Complex Domestication History of the Cultivated Tomato in Latin America. *Molecular Biology and Evolution* **37**(4):1118–32. https://doi.org/10.1093/molbev/msz297

Rönspies, M., Schindele, P., & Puchta, H. (2021). CRISPR/Cas-mediated chromosome engineering: Opening up a new avenue for plant breeding. In *Journal of Experimental Botany* **72**(2): 177–183. https://doi.org/10.1093/jxb/eraa463

Roohanitaziani, R., de Maagd, R. A., Lammers, M., Molthoff, J., Meijer-Dekens, F., van Kaauwen, M. P. W., Finkers, R., Tikunov, Y., Visser, R. G. F., & Bovy, A. G. (2020). Exploration of a resequenced tomato core collection for phenotypic and genotypic variation in plant growth and fruit quality traits. *Genes* **11**(11): 1–22. https://doi.org/10.3390/genes11111278

Rose, L. E., Zangishei, Z., Fernie, A. R., & Usadel, B. (2025). Tomato and its relatives are breaking the genomics barriers. *Journal of Experimental Botany*. https://doi.org/10.1093/jxb/eraf298

RVO Netherlands. (2023). *Tomato Value Chain Report – Ghana*. https://projects.rvo.nl/sites/default/files/rvo_website_content/opendata/iati/CATK/CST23GH01_01.pdf

Sánchez-Bermúdez, M., del Pozo, J. C., & Pernas, M. (2022). Effects of Combined Abiotic Stresses Related to Climate Change on Root Growth in Crops. In *Frontiers in Plant Science* (Vol. 13). Frontiers Media S.A. https://doi.org/10.3389/fpls.2022.918537

Schreinemachers, P., Ambali, M., Mwambi, M., Olanipekun, C. I., Yegbemey, R. N., & Wopereis, M. C. S. (n.d.). *The Dynamics of Africa's Fruit and Vegetable Processing Sectors*. Retrieved http://www.fao.org/faostat/en/#data

Sharma, P., Thakur, S., & Negi, R. (2019). Recent Advances in Breeding of Tomato- A Review. *International Journal of Current Microbiology and Applied Sciences*, **8**(03), 1275–83. https://doi.org/10.20546/ijcmas.2019.803.151

Soresa, D. N., Nayagam, G., Bacha, N., & Jaleta, Z. (2020). Heterosis in Tomato (Solanum lycopersicum L.) for Yield and Yield Component Traits. *Advances in Research* 141–152. https://doi.org/10.9734/air/2020/v21i930242

Temesgen, B., & Temesgen, T. (2024). Genetic Variability and Its Benefits in Crop Improvement: A review. *Middle East Journal of Agriculture Research*. https://doi.org/10.36632/mejar/2024.13.1.6

Thapa, S. P., Miyao, E. M., Michael Davis, R., & Coaker, G. (2015). Identification of QTLs controlling resistance to Pseudomonas syringae pv. tomato race 1 strains from the wild tomato, Solanum habrochaites LA1777. *Theoretical and Applied Genetics* **128**(4): 681–692. https://doi.org/10.1007/s00122-015-2463-7

Tieman, D., Zhu, G., Resende, M. F. R., Lin, T., Nguyen, C., Bies, D., Rambla, J. L., Stephanie, K., Beltran, O., Taylor, M., Zhang, B., Ikeda, H., Liu, Z., Fisher, J., Zemach, I., Monforte, A., Zamir, D., Granell, A., Kirst, M., ... Klee, H. (2017). PLANT SCIENCE A chemical genetic roadmap to improved tomato flavor. *Science* **355**. http://science.sciencemag.org/

Tiwari, J. K., Singh, A. K., & Behera, T. K. (2023). CRISPR/Cas genome editing in tomato improvement: Advances and applications. *Frontiers in Plant Science* **14**. https://doi.org/10.3389/fpls.2023.1121209

Tripodi, P., Soler, S., Campanelli, G., Díez, M. J., Esposito, S., Sestili, S., Figàs, M. R., Leteo, F., Casanova, C., Platani, C., Soler, E., Bertone, A., Pereira-Dias, L., Palma, D., Burguet, R., Pepe, A., Rosa-Martínez, E., Prohens, J., & Cardi, T. (2021). Genome wide association mapping for agronomic, fruit quality, and root architectural traits in tomato under organic farming conditions. *BMC Plant Biology* **21**(1). https://doi.org/10.1186/s12870-021-03271-4

Tripodi, P., Vitiello, A., D'Onofrio, B., Parisi, M., & Cammareri, M. (2020). Dissecting the genotypic and environmental factors underpinning the quantitative trait variation in a set of wild tomato (Solanum habrochaites LA1777) introgression lines. *Agronomy* **11**(1). https://doi.org/10.3390/agronomy11010038

Tsutsumi-Morita, Y., Heuvelink, E., Khaleghi, S., Bustos-Korts, D., Marcelis, L. F. M., Vermeer, K. M. C. A., Van Dijk, H., Millenaar, F. F., Van Voorn, G. A. K., & Van Eeuwijk, F. A. (2021). Yield dissection models to improve yield: A case study in tomato. *In Silico Plants* **3**(1). https://doi.org/10.1093/insilicoplants/diab012

Tyagi, A., Mir, Z. A., Almalki, M. A., Deshmukh, R., & Ali, S. (2024). Genomics-Assisted Breeding: A Powerful Breeding Approach for Improving Plant Growth and Stress Resilience. In *Agronomy* **14**(6). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/agronomy14061128

Villanueva Gutierrez, E. E. (2018). *An overview of recent studies of tomato (Solanum lycopersicum spp) from a social, biochemical and genetic perspective on quality parameters*. https://pub.epsilon.slu.se

Vu, T. Van, Das, S., Tran, M. T., Hong, J. C., & Kim, J. Y. (2020). Precision Genome Engineering for the Breeding of Tomatoes: Recent Progress and Future Perspectives. In: *Frontiers in Genome Editing*. **2**. Frontiers Media S.A. https://doi.org/10.3389/fgeed.2020.612137

Waiba, K. M., Sharma, P., Kumar, K. I., & Chauhan, S. (2021). Studies of Genetic Variability of Tomato (Solanum lycopersicum L.) Hybrids under Protected Environment. *International Journal of Bio-Resource and Stress Management* **12**(5): 264–70. https://doi.org/10.23910/1.2021.2211

Worku, M., De Groote, H., Munyua, B., Makumbi, D., Owino, F., Crossa, J., Beyene, Y., Mugo, S., Jumbo, M., Asea, G., Mutinda, C., Kwemoi, D. B., Woyengo, V., Olsen, M., & Prasanna, B. M. (2020). On-farm performance and farmers' participatory assessment of new stress-tolerant maize hybrids in Eastern Africa. *Field Crops Research* **246**. https://doi.org/10.1016/j.fcr.2019.107693

World Food and Agriculture. (2024). World Food and Agriculture – Statistical Yearbook 2024. In: *World Food and Agriculture – Statistical Yearbook 2024*. FAO. https://doi.org/10.4060/cd2971en

Xu, R., & Li, C. (2022). A Review of High-Throughput Field Phenotyping Systems: Focusing on Ground

Robots. In *Plant Phenomics* **2022**. https://doi.org/10.34133/2022/9760269

Xu, W., Gong, C., Mai, P., Li, Z., Sun, B., & Li, T. (2024). Genetic diversity and population structure analysis of 418 tomato cultivars based on single nucleotide polymorphism markers. *Frontiers in Plant Science*, **15**. https://doi.org/10.3389/fpls.2024.1445734

Yali, W. (2022). Molecular Markers: Their Importance, Types, and Applications in Modern Agriculture. *Agriculture, Forestry and Fisheries*, **11**(1): 8. https://doi.org/10.11648/j.aff.20221101.12

Yeon, J., Nguyen, T. T. P., Kim, M., & Sim, S. C. (2024). Prediction accuracy of genomic estimated breeding values for fruit traits in cultivated tomato (Solanum lycopersicum L.). *BMC Plant Biology*, **24**(1). https://doi.org/10.1186/s12870-024-04934-8

Yongsuwan, A., Poncheewin, W., Sastawittaya, W., Somkul, A., Thunnom, B., Aesomnuk, W., Bhunchoth, A., Phironrit, N., Phuangrat, B., Koohapitakthum, R., Deeto, R., Warin, N., Wanchana, S., Arikit, S., Chatchawankanphanich, O., Chuenwarin, P., & Ruanjaichon, V. (2024). Exploring the Genomic Landscape: A Comprehensive Analysis of the Genetic Diversity and Population Structure of Thai Tomato Germplasm through Whole-Genome Sequencing (WGS). *Horticulturae*, **10**(6). https://doi.org/10.3390/horticulturae10060602

Zhang, J., Liu, S., Zhu, X., Chang, Y., Wang, C., Ma, N., Wang, J., Zhang, X., Lyu, J., & Xie, J. (2023). A Comprehensive Evaluation of Tomato Fruit Quality and Identification of Volatile Compounds. *Plants*, **12**(16). https://doi.org/10.3390/plants12162947

Zhou, Y., Zhang, Z., Bao, Z., Li, H., Lyu, Y., Zan, Y., Wu, Y., Cheng, L., Fang, Y., Wu, K., Zhang, J., Lyu, H., Lin, T., Gao, Q., Saha, S., Mueller, L., Fei, Z., Städler, T., Xu, S., … Huang, S. (2022). Graph pangenome captures missing heritability and empowers tomato breeding. *Nature*, **606**(7914): 527–534. https://doi.org/10.1038/s41586-022-04808-9

Zsögön, A., Čermák, T., Naves, E. R., Notini, M. M., Edel, K. H., Weinl, S., & al., et. (2018). De novo domestication of wild tomato using genome editing. *Nature Biotechnology*, 36: 1211–1216. https://doi.org/10.1038/nbt.4272

Current Horticulture **14**(2): 16-22, April–June 2026
DOI:
Received: 20 August 2025; Accepted: 17 June 2026

Fruit-bud differentiation in grapevine *(Vitis vinifera)* : a review

R.G. Somkuwar[1] and Rutuja Nale[2*]

[1]ICAR- National Research Centre for Grapes, Pune, Maharashtra, India

Abstract

Grapevine (*Vitis vinifera* L.) reproductive development extends over two growing seasons (vegetative cycles) for complete formation of inflorescences and clusters, and reproductive cycle (development of a cluster). The process of induction and floral differentiation, which leads to creation of reproductive structures within dormant buds, is intricate and occurs in three distinct stages: formation of anlagen, inflorescence primordia, and flowers. This sequence of stages involves morphological, biochemical, and physiological changes, all influenced by a range of environmental and internal factors. The review describes the morphology and physiology of fruit-bud differentiation, as well as discusses the main abiotic and biotic factors involved.

Key words: Bud differentiation, Grapevine, Inflorescence primordia, Potential yield

Grape (*Vitis vinifera* L.) is a major important fruit crop of our country, especially in the peninsular region, where its vines are pruned twice a year. In April, vines are pruned to encourage shoot growth, cane development, fruit-bud formation, and reserve storage in the cane. In October, shoots are pruned to promote fruiting for a more yield. The number of bunches on a vine indicates its yield, which is determined by fruitfulness of the canes. Yield is influenced by the number of flower clusters per unit area and average weight of clusters. The fruitfulness of the canes is determined after back pruning, the yield being reliant on cultural practices carried out between April and September. Thus, a fruiting cane is considered the unit of production.

The productivity refers to grapevine's inherent ability to produce the maximum yield, which varies across different varieties. There is often a significant gap between vine's potential productivity and actual yield, which can be improved through various cultural practices such as crop regulation, use of growth regulators, training, canopy management, and pest and disease management.

Bud development

As shoots develop throughout the growing season, buds appear in the leaf axil (at the base of the petiole). The initial bud to form in the leaf axil is the lateral bud, which grows into a lateral shoot during the first growing season. This lateral shoot may either fail to lignify and drop off the vine in autumn or winter, or it may lignify and stay on vine through dormancy. If the bud does not grow in the first season, it dies. The first leaf of lateral bud is reduced to a prophyll, a modified leaf that differs from the typical leaves along the shoot. A second bud forms in the axil of this prophyll, known as the compound bud. The compound bud develops gradually, depending on grapevine variety, it may produce 10 - 12 leaf primordia before entering into dormancy. It can also generate one to three cluster primordia during this time, again depending on variety. Several bracts, which are modified leaves, form at the base of this bud before the first leaf primordium appears. Secondary and tertiary buds develop in axils of these bracts. Therefore, compound bud contains three distinct buds. The primary, secondary, and tertiary buds are surrounded by basal bract or prophyll of lateral bud or shoot. Together, these elements form the prominent compound bud (eye) found on mature canes at a node. Although commonly called the latent bud in singular form, it is a compound bud, with each individual bud situated in the leaf axil of another. While compound or fruit bud may seem to be located in the axil of the cane from the primary shoot, it is actually a basal extension of the lateral bud or shoot. The compound bud and lateral bud or shoot are closely linked, with vascular tissue (xylem vessels) from the young compound buds connecting directly to the lateral bud.

Corresponding author : rutujanale2502@gmail.com
[2] Department of Horticulture, MPKV, Rahuri, Ahilyanagar, Maharashtra, India

Flowering

The formation of inflorescence and flowers involves three well-defined stages:

Formation of anlagen: Anlagen are club-shaped meristematic protuberances which arises from the apices of latent bud. Anlagen are uncommitted primordia which may be directed to from inflorescence primordia, tendril primordia or shoot primordia. Formation of anlagen is also referred to as inflorescence initiation or inflorescence axis formation.

Formation of inflorescence primordia: Anlagen which have been directed to develop as inflorescences undergo repeated branching to form a conical structure composed of many rounded branch primordia.

Formation of flowers: Differentiation of inflorescence primordia to form the individual flowers.

Grapevine bud fruitfulness

Bud fruitfulness refers to potential of a bud to produce an inflorescence, often quantified by number of inflorescence primordia per bud. Bud fertility, typically assessed by number of bunches or fruit weight per node, provides a more practical measure of productivity (Dry, 2000). Bud fertility varies in latent buds based on their position on the cane: it increases from the base to the middle and then decreases toward the apex. Improper bud development during the growth cycle accounts for 60% of the seasonal yield variation in vineyards. A critical point in grapevine reproductive development occurs when the anlage splits into two parts (inner and outer), determining whether they will produce inflorescence or tendril primordia (Dunn and Martin, 2007). Earlier initiation of anlage results in earlier primary branching and the start of inflorescence primordium development.

The degree of inflorescence primordium differentiation in the primary axis of a latent bud follows an acropetal gradient (Li-Mallet *et al*., 2016; Cheema *et al*., 1996). Understanding the regulation of inflorescence initiation and differentiation is key to controlling bud fruitfulness and grapevine yield. These processes are influenced by numerous environmental factors, e.g. temperature, light, and water status and internal factors such as sugar and mineral nutrition, their metabolism, hormones, and gene regulation. Environmental factors, which are the main contributors to yield variability are difficult to control. They affect not only the initiation and differentiation of inflorescence primordia but also the plants overall physiological functions, including nutrient assimilation, metabolism, and hormonal balance.

Factors affecting fruit-bud differentiations

Environmental factors

Numerous studies have been conducted on the effects of environmental conditions on inflorescence, flower formation, and grapevine fruitfulness (Clingeleffer *et al*., 2001; Sánchez and Dokoozlian 2005; Carmona *et al*., 2008; Al-Obeed *et al*., 2010; Guilpart *et al*., 2014; Somkuwar *et al*., 2014). Induction of inflorescences in grapevine is not sensitive to vernalization, which is usually involved in flower formation in herbaceous plants (Carmona *et al*., 2008). Although the effect of photoperiod is not well understood, short-term exposure of grapevine to high temperature and high light intensity can promote grapefruit fruitfulness.

Temperature

Many reports have indicated that inflorescence primordia formation requires high temperatures (Dunn and Martin 2000; Petrie and Clingeleffer 2005). There is correlation between the temperature during the initiation stage of the inflorescence primordia and number of inflorescences appearing on the shoot (Guilpart *et al*., 2014). In the temperate region, the fruit bud differentiation take place in next year on current season's growth whereas it happens during the period of 30-60 days after foundation pruning (back pruning) on current season's growth in peninsular India. Temperature appears to be more favorable than light for fruitfulness of Thompson Seedless bud or higher light intensities than 3600 ft. candles above 35°C could be favorable for fruitfulness of the bud (Somkuwar, 2005).

According to Chadha and Shikhamany (1999), the critical level of temperature and light for bud fruitfulness in Thompson Seedless is 35°C and 3600 ft candles respectively. Buttrose (1969) noted that in a temperature controlled environment with different varieties (Almeria, Muscat of Alexandria, Riesling, Syrah, and Thompson Seedless) have shown that the optimum temperature interval for formation of inflorescence varies from 20 to 35°C. At temperatures below 20°C tendrils are formed, reducing the growth and yield. On the other hand, temperatures above 30 °C for at least 4 - 5 hr per day should be sufficient to induce a maximum number of inflorescence (Srinivasan and Mullins, 1980).

Various authors have demonstrated opposite effects, with a decrease in bud fruitfulness under high temperatures. Sharma *et al*., (2018) noted that as temperature increases more than 40°C during bud fruitfulness will lead to delayed and erratic bud sprouts and also reduces the fruit bud differentiation. High temperature negatively affects plant growth and survival and hence crop yield. According to Pouget (1981), higher temperatures lead to rapid growth of vegetative organs in the developing shoot, which increases the speed of bud break and consequently fewer flowers are formed.

The mechanism by which temperature affects the initiation of inflorescences remains unclear, although some hypotheses have been proposed. The influence of temperature on the biosynthesis of gibberellins (GAs) and cytokinins (CKs) is one of the possible explanations. May (1987) suggested that higher temperature may increase cytokinins levels in precocious flowers, thereby inhibiting the formation of other flowers. Temperatures ranging from 25°C to 35°C promote cytokinins biosynthesis, which is known to stimulate inflorescence differentiation (Jackson, 2014). Low temperatures (20°C) promote

GA biosynthesis, which promotes vegetative growth and reduces nutrient accumulation. The influence of temperature on biochemical processes such as photosynthesis, enzymatic activity, and respiratory activity has also been hypothesized (Taiz, 2006; Keller, 2015). The optimal temperature range for photosynthesis varies between 25°C and 30°C depending on the variety and phenology. Temperatures above 35°C negatively affect photosynthesis as the stomata begin to close (Somkuwar *et al.,* 2018; Monteiro *et al.,* 2021).

Light

In herbaceous plants, different light characteristics such as light quality, light intensity, and photoperiod influence the number of inflorescences, flower induction, and differentiation. Unlike herbaceous plants, there was no significant effect of red: far-red ratio on grapevine bud fruitfulness in terms of light quality (Sommer *et al.*, 2000). Light intensity is essential factor for initiation and differentiation of dormant bud (Buttrose, 1969; Dry, 2000; Vasconcelos *et al.*, 2009). Correlation between light intensity and fruitfulness (number of inflorescences per shoot) of buds in Sultana grapevine was first time noted by Antcliff and May (1961). Increases in number of inflorescence primordia with light intensity under controlled climatic condition was reported by Buttrose (1969) and Sanchez and Dokoozlian (2005).

Light may have an influence on fruitfulness through its effect on photosynthesis and carbohydrate availability, or it may have a direct effect on the bud fruitfulness. Lebon *et al.*, (2008) observed decease in emergence of primary and secondary bud due to low light intensity which reduces the amount of photoassimilates and limiting the carbohydrates supplies to emerging bud. Kriedman and Smart (1971) found that light intensity required for maximum photosynthesis in Thompson Seedless ranges from 2500 to 5000 ft candles. If the light intensity is more than 5000 ft candles, leaf loses its chlorophyll by photo oxidation. Depending on the cultivar or species, the sensitivity of bud fruitfulness to light exposure is different. The effects of photoperiod on the initiation and differentiation of inflorescence primordia are unclear; however, in some varieties, the number of inflorescence primordia appears to be greater on long days than on short days (Vasconcelos *et al.*, 2009)

Water condition

Water status affects bud fruitfulness indirectly through altering plant hormone balance, mineral nutrition, microclimate around the bud, and vine photosynthesis (carbohydrate production). Directly, it affects bud fruitfulness through the amount of water available for the biosynthetic processes occurring during cell division and enlargement (Williams, 2000; Jackson, 2014; Li Mallet *et al.*, 2016). Water deficiency and excessive water are two characteristics of water status that have a major impact on the fruitfulness of dormant buds during the growing season. An increase in bud fruitfulness is a result of enhanced inflorescence differentiation conditions, especially due to an adequate water availability.

On the other hand, when there is water stress, inflorescence size and number are significantly impacted. When water is limited, photosynthesis decreases and may hinders the production of sufficient carbohydrates for inflorescence development. Reducing canopy density under moderate water stress can boost bud fruitfulness by raising light exposure, predominantly in the renewal zone. Water stress leads to an imbalance in xylem sap hormones, resulting in a decrease in cytokinins and an increase in abscisic acid, which negatively affects differentiation. Stomatal closure, induced by elevated ABA, hinders photosynthesis in response to water stress. The differentiation of inflorescences is also sensitive to the combined effects of nitrogen deficiency and water stress (Osakabe *et al.*, 2014; Guilpart *et al.*, 2014).

Rainfall

The rainfall in grape growing area has direct impact on the fruitfulness. A rain during the stage of fruit bud differentiation (40 - 60 days after back pruning) is not favorable for grape since the excessive shoot growth hamper the initiation of floral primordial. The only alternative will be to adjust the pruning time in such a way that the rainy season will not coincide with the important growth stage like fruit bud differentiation (Somkuwar, 2005).

Relative humidity

For the grape to grow and develop, it needs a warm and dry climate. As a result, highly humid conditions are not conducive to any stage of vine growth and fruitfulness. Bud differentiation takes place between May and June if the vines are pruned in April, during which a dry atmosphere with low relative humidity prevails. Therefore, after back-pruning, the high humidity problem is not a constraint. However, rainfall in combination with high humidity during foundation pruning may delay bud break and increase the risk of diseases.

Nutrient availability

The significance of nutrition in determining vine productivity is well-established. Proper quantity of macronutrients (nitrogen, phosphorus, and potassium) are essential for maximum floral induction, differentiation, and fruitfulness. Phosphorus plays a crucial role in flowering by synthesizing proteins and nucleic acids favorable for inflorescence development. This process influences carbon dioxide absorption, cell membrane establishment, and the relocation of essential structures. Energy storage and transfer are influenced by its role as well (Adam Jacobs, 2002) 30 days after pruning, phosphorous application enhances bud fruitfulness. Zinc like phosphorus is essential during fruit bud differentiation, contributing to increased RNA synthesis and ultimately, fruitfulness. As per Rao and Srinivasan (1971), the rate of RNA syntheses and ratio of RNA/ DNA was higher in fruitful buds.

Nitrogen is vital for constructing amino acids used in building structural proteins and enzymes, as well as facilitating all biochemical reactions. Chlorophyll and hormones share a common constituent (Keller, 2015). Following nitrogen application, low nitrogen grapevines generated more inflorescences and flowers. About 30-60 days after pruning, avoid using nitrogenous fertilizer to prevent excess cane growth. For the first 30 days after pruning, nitrogen is vital for producing new growth structures in plants. Application of excess nitrogen during this phase hinders flower bud initiation by promoting vegetative growth and casting a shading effect. Potassium plays a vital role in enzyme activation, photosynthesis, and efficient plant water management. Applying K to the soil increased the fruitfulness of Thompson Seedless grapes.

Other factors

Canopy management

Efficient canopy management practices significantly contribute to seasonal sustainability in commercial vineyards. A number of practices are used to improve canopy structure for optimal photosynthesis, balance vegetative and reproductive growth, and ensure sufficient sunlight exposure (Smart and Robinson, 1991; Coombe and Dry, 1994). Proper canopy management practices enhance the late spring microclimate, promoting inflorescence primordia formation by increasing light intensity and temperature (Buttrose, 1969; Dry, 2000; Sánchez and Dokoozlian, 2005). Bud fruitfulness may be improved by light as a result of its effect on photosynthesis and subsequent carbohydrate production or a direct effect on the bud itself (Vasconcelos *et al.*, 2009; Li-Mallet *et al.*, 2016). Any lapses during the critical stages of growth may lead to barrenness of the vine. Therefor number of shoots, its orientation, partial defoliation, tipping and use of growth retardants are some of the important considerations need to be followed in the canopy management.

Number of shoots/vine

After back pruning, approximately 70-80 shoots sprout on each vine. If all the shoots are allowed to grow, there will be competition for nutrients, water, and sunlight. The fruitfulness of the bud depends on exposure to sunlight during the bud differentiation stage. Excess shoots create the shading effect, thus reducing photosynthetic activity. The leaves of such shoots become yellow and drop down leading to immature canes. Such canes do not contain fruitful buds; hence, they are removed at the time of fruit pruning. To avoid green canes during the maturity stage, shoot thinning is recommended at the 4–5 leaf stage after back pruning. This helps to avoid crowding of shoots, proper aeration and maximum sunlight harvest for bud differentiation. This type of canopy also avoids the incidence of diseases. For export markets, cane density should be 0.7 canes/sq. ft areas during the periods of back pruning and one cane for domestic markets.

Shoot vigor

The growth arising from the sprouted bud is called shoot. The shoot growth is by cell division and cell elongation. Increases in the shoot length per day is termed as rate of shoot growth. The shoot grows faster during the first 30 days of back pruning. This period is called as grand growth period. Vigor of the shoot or the rate of growth is considered more when the time required to produce an extra leaf is less (Shikhamany, 1999). During the grand period of growth, the rate of shoot growth on the renewal spurs is more than that on the fruiting canes. The duration of shoot growth also varies with the variety and the climatic condition prevailing in the area. During the grand growth period, if the growth is not controlled, there will be an increase in internodal distance and shoot length. Vigorous shoot growth led to reduced fruitfulness that results in fillage i.e. conversion of fruitful bud into tendril.

Position of shoot (horizontal vs. vertical)

Shoot orientation should be in such a way that each bud on shoot gets maximum available sunlight. Training grapes to trellis such as Geneva Double Curtain (GDC), Y-trellis and Tatura result in open canopies with diagonal shoot orientation to harvest more sunlight by individual buds on the shoot. Beside the foliar density, the angle of the shoot with the horizontal surface influences the light interception. Long and thin shoot bend by its own weight narrowing the angle while the short and thick shoot tend to be erect increasing the angle and thereby more light interception in the canopy. The vertically grown shoot is exposed to the full sunlight uniformly. (Somkuwar and Ramteke, 2008) studied effect of shoot orientation on fruitfulness in Thompson Seedless and reported that high bud fruitfulness in vertically oriented shoot due to maximum chlorophyll content in leaves. On the other hand, horizontally positioned shoots will not receive the light equally for bud differentiation and its maturity.

Cane thickness

There is a positive correlation of fruitfulness with cane diameter and position of shoot on the training system (Somkuwar and Ramteke, 2008). The thick cane at the beginning becomes erect and thus helps in receiving the required sunlight uniformly on every bud of the shoot. With the increases in the cane thickness, the bud size increases but the time taken for bud sprouting also increases. More than the size of the cane, the quality of cane is also important for bud fruitfulness.

Training system

Training system plays an important role in the fruitfulness and substantially enhances productivity. The position of shoot is determined by the training system. May training systems have been developed in the past and others are being developed to adopt vine growth to the climate and cultural conditions. Studies indicate that upward growing shoots are normally more fruitful than the downward shoots. The trellis system has a critical role in the canopy management principles, the training system must allow a uniformly distributed canopy with sufficient sunlight penetration for the continued production of healthy and equally ripened grapes of high quality (Smart, 1982; Smart *et al*., 1990; Hunter, 1999).

Bower system

In India, grapevines are commonly trained using the low-cost bower (Pandal) system. This system creates challenges for cultural operations. In this system, where the canopy is horizontal, more secondary shoots with their attached shoots are retained. The excessive foliage in the vine canopy limits the amount of sunlight it intercepts. Inadequate light negatively impacts both bud productivity and shoot maturity by inducing early leaf drop. The system promotes a favorable microclimate for the growth of fungal diseases such as downy mildew.

Flat roof gable

In this training system, the canopy is trained vertically and therefore there is a scope to harvest maximum sunlight by individual shoot uniformly. The percentage of mature and fruitful canes are always more than the bower trained vines. Cultural practices are also easy in this system. Proper aeration in the vine canopy

Table 1: Comparison of fruitful canes in bower and flat roof gable system of training

Character	Bower	FRG
No. of canes/vine	More	Less
Canopy architecture	Vertical	Vertical
Percent green shoots	More	Less
Percent mature shoots	Less	More
Percent fruitful canes/vine	Less	More

prevent disease spread.

Kniffin system

A vertical trellis with horizontal wires is used for grapevine training, allowing for effective vine support and canopy management. In the Modified Kniffin system, optimal vine support and improved airflow lead to enhanced bud development and fruitfulness. Pruning and training are necessary for optimal fruit production and to prevent overcrowding.

Rootstocks

The introduction of rootstocks in grape cultivation is of recent origin. The increasing problem of soil salinity and drought felt the need of rootstock. The rootstock has the potential to sustain under adverse situation and manipulation of vine growth and production. Rootstocks play an important role in maintaining equilibrium between growth and yield. Increase in yield is mainly due to increase in fruitfulness of the vine under given set of condition. Direct effect of rootstocks on fruit bud differentiation and consequently on yield is attributed to the capacity of rootstock to synthesize the cytokinins. It is well known fact that cytokinins are synthesized in roots and high cytokinin/gibberellins ratio was found to be favorable for fruit bud formation. Somkuwar *et al*., (2006) noted that bud fruitfulness in relation to different rootstock showed that the variety Thompson Seedless grafted on 110-R rootstock produced more fruitful canes than other rootstocks.

CONCLUSION

Current environmental conditions significantly influence inflorescence initiation, differentiation, and bud fertility, accounting for approximately 60% of total crop yield variation. Temperature, light, and water status significantly impact the physiological function of a vine from budbreak to bloom. A healthy grapevine requires optimal biosynthesis, energy storage, and mineral absorption, especially for bud and inflorescence development. The regulatory mechanisms of bud fruitfulness in response to both exogenous and endogenous factors are not well understood. The application of plant growth regulator promoted inflorescence initiation, differentiation, and development. Both high and low concentrations elicit adverse effects. The stage of bud development influences the adverse effects of PGR. The regulation of bud differentiation is not well understood in terms of PGR and PGR balance. More research is needed to understand the mechanism behind inflorescence initiation and differentiation using a combination of various approaches. Because early yield estimation based on bud fruitfulness is a useful tool for viticulturists.

REFERENCES

Anticliff A and May P. 1961 Dormancy and bud burst in Sultana vine. *Vitis* **3**: 1–14.

Al-Obeed R S, Kassem H A and Ahmed M A. 2010. Effect of grapevine varietal differences on bud fertility, yield and fruit quality under arid environments and domestic wastewater irrigation. *American-Eurasian Journal of Agricultural & Environmental Sciences* **9**: 248–55

Buttrose M S. 1969. Fruitfulness in grapevines: Effects of light intensity and temperature. *Botanical Gazette* **130 (**3): 166-73.

Carmona M J, Chaïb J, Martínez-Zapater J M and Thomas M R. 2008. A molecular genetic perspective of reproductive development in grapevine. *Journal of Experimental Botany* **59**: 2579–96.

Chadha K L and Shikhamany S D. 1999. *The grape: improvement, production and post-harvest management.*

Cheema S S, Torregrosa L, Domergue P and Carbonneau A. 1996. A comparative study of the differentiation of inflorescence and flower of Vitis vinifera L. cv. Syrah in situ and under greenhouse conditions. Progres Agricole et Viticole (France) **113:** 279–285.

Clingeleffer P R, Martin S, Krstic M, and Dunn G M. 2001. Crop development, crop estimation and crop control to secure quality and production of major wine grape varieties: A national approach (No. CSH 96/1). Grape and Wine Research & Development Corporation.

Coombe B G and Dry P R. 1992. *Viticulture*, Volume 2. Practices.

Dry, P. R. 2000. Canopy management for fruitfulness. *Australian Journal of Grape and Wine Research***6 (2):** 109-15.

Dry P and Coombe B. 1994. Primary bud-axis necrosis of grapevines. I: Natural incidence and correlation with vigour. *Vitis* **33:** 225–30.

Dunn G M and Martin S R. 2007. A functional association in *Vitis vinifera* L. cv. Cabernet Sauvignon between the extent of primary branching and the number of flowers formed per inflorescence. *Australian Journal of Grape and Wine Research* **13:** 95–100.

Dunn G M and Martin S R. 2000. Do temperature conditions at budburst affect flower number in Vitis vinifera L. cv. Cabernet Sauvignon? *Australian Journal of Grape and Wine Research* **6**: 116–12

Guilpart N, Metay A and Gary C. 2014. Grapevine bud fertility and number of berries per bunch are determined by water and nitrogen stress around flowering in the previous year. *European Journal of Agronomy* **54:** 9–20.

Hunter J J. 1999. Present status and prospects of winegrape viticulture in South Africa: focus on canopy related aspects/practices and relationships with grape and wine quality. In: *Gesco: groupe d'etude des systèmes de conduite de la vigne* pp. 70-85.

Jacobs, A. 2002. A balanced approach to vine nutrition. *Australian and New Zealand grapegrower and winemaker* **466:** 22-25.

Jackson, R.S. 2014. Wine Science: Principles and Applications, 4th ed.; Academic Press: Cambridge, MA, USA.

Keller, M. 2015. Phenology and growth cycle. *The science of grapevines* ***2:*** 59-99.

Li-Mallet A, Rabot A and Geny L. 2016. Factors controlling inflorescence primordia formation of grapevine: their role in latent bud fruitfulness? A review. *Botany* **94(3):** 147-63.

Lebon G, Wojnarowiez G, Holzapfel B, Fontaine F, Vaillant-Gaveau N and Clement C.2008. Sugars and flowering in the grapevine (*Vitis vinifera* L.). *Journal of Experimental Botany* **59:** 2565–78.

May, P. 1987. The grapevine as a perennial, plastic and productive plant. In *Proceedings of the Sixth Australian Wine Industry Technical Conference,* pp. 40-49.

Monteiro A I, Malheiro A C and Bacelar E A. 2021. Morphology, physiology and analysis techniques of grapevine bud fruitfulness: A review. *Agriculture* **11(2):** 127.

Osakabe Y, Osakabe K, Shinozaki K and Tran L S. 2014. Response of plants to water stress. *Frontiers in Plant Science* **5**: 86.

Petrie P R and Clingeleffer P R. 2005. Effects of temperature and light (before and after budburst) on inflorescence morphology and flower number of Chardonnay grapevines (*Vitis vinifera* L.). *Australian Journal of Grape Wine Research* **11:** 59–65.

Pouget, R. 1981. Action de la température sur la différenciation des inflorescences et des fleurs durant les phases de predébourrement et de post-débourrement des bourgeons latents de la vigne. Connaissance de la Vigne et du Vin, 15: 65–79.

Rao V M and Srinivasan C. 1971. Nucleic acid composition in the developing buds and petioles of grapes. *Vitis* **10:** 210-14.

Sommer K J, Islam M T and Clingeleffer P R. 2000. Light and temperature effects on shoot fruitfulness in Vitis vinifera L. cv. Sultana: Influence of trellis type and grafting. *Australian Journal of Grape Wine Research* **6**: 99–108.

Somkuwar, R.G. 2005. Fruitfulness in grape. Technical Bulletin No. 8

Somkuwar R G, Sharma J, Satisha J, Ramteke S D, Khan I and Itroutwar P. 2014. Growth, fruitfulness and yield in relation to mycorrhizal inoculants in Thompson Seedless grapes (*Vitis vinifera* L.) grafted on Dog Ridge rootstock. *Progressive Horticulture* **46(1):** 23-30.

Somkuwar R G, Satisha J and Ramteke S D. 2006. Effect of different rootstocks on fruitfulness in Thompson Seedless (*Vitis vinifera* L.) Grapes. *Asian Journal of Plant Sciences* **5(1):** 150-52.

Somkuwar R G and Ramteke S D. 2008. Effect of shoot orientation on growth, biochemical changes and fruitfulness in Thompson Seedless (*Vitis vinifera* L.) grapes. *Journal of Plant Science* **3(2):** 182-87.

Smart, R.E. 1980. Vine manipulation to improve wine grape quality. In: *Proc. Grape and Wine Centennial Symp,* pp. 362-75.

Smart R E, Dick J K, Gravett I M and Fisher B M. 1990. Canopy management to improve grape yield and wine quality-principles and practices. *South African Journal of Enology and Viticulture* **11(1):** 3-17.

Sharma A K, Somkuwar R G, Banerjee K, Jogaiah S and Kamble N. 2018. Crop levels and pruning timing affect must and wine quality of Cabernet Sauvignon wine grape. *Indian Journal of Horticulture* **75**(03)**:** 384-91.

Sommer, K.J., Islam, M.T., and Clingeleffer, P.R. 2000. Light and temperature effects on shoot fruitfulness in Vitis vinifera L. cv. Sultana: Influence of trellis type and grafting. *Australian Journal of Grape Wine Research* **6:** 99–108.

Smart R and Robinson M. 1991. *Sunlight into wine: a handbook for winegrape canopy management*. Winetitles. Underable, SA, Australia.

Sánchez L A and Dokoozlian N K. 2005. Bud microclimate and fruitfulness in Vitis vinifera L. *American Journal of Enology and Viticulture* **56(4):** 319-29.

Srinivasan C and Mullins M G. 1980. Effects of temperature and growth regulators on formation of anlagen, tendrils and inflorescences in *Vitis vinifera* L. *Annals of Botany* **45(4):** 439-46.

Taiz L and Zeiger E. 2006. Plant. Physiology, 4th ed.; Sinauer Associates: Sunderland, MS, USA,

Vasconcelos M C, Greven M, Winefield C S, Trought M C and Raw V. 2009. The flowering process of Vitis vinifera: a review. *American Journal of Enology and Viticulture* ***60***(4)**:** 411-434.

Williams, L.E. 2000. Bud development and fruitfulness of grapevines. In Raisin Production Manual. UCANR Publications, Calif, pp. 24–29.

Current Horticulture **14**(2): 23-35, April–June 2026
DOI: 10.5958/2455-7560.2026.00017.7
Received: 2 June 2026; Accepted: 17 June 2026

Microirrigation and fertigation in citrus (*Citrus* spp.): chronological advances

P. S. Shirgure

ICAR- National Research Centre on Pomegranate, Solapur 413 255, Maharashtra, India

Abstract

Citrus (*Citrus* spp.) belongs to an evergreen tree category, requires some kind of stress , either soil water deficit stress or low temperature stress for induction of flowering, depending upon agro-pedology of growing conditions. Soil physical properties participate to a greater extent in regulating the success of flowering , fruit setting intensity and yield, coupled with desirable quality traits compared to chemical properties with regard to fertilizers- and water-use-efficiency. Hence, water management via micro-irrigation and fertigation play a pivotal roles in production sustainability alongside orchard longevity. A number of studies have established varying savings (25-35%) on both fertilizers and irrigation water compared to overly tilted use of basin irrigation methods. Computation on stagewise nutrient and water application scheduling without compromising the recommended doses of fertilizers and irrigation has further aided in developing precision citriculture with reduced water footprints and improved water-and nutrient-use-efficiency. However, carbon footprint emphasizing soil-plant-environment inclusive studies in relation to coupling of irrigation and fertilization is still not a preferred research agenda , in addition to development of 4R (right amount of fertilizers at right growth stage in right form and right placement) 4W (right amount of water at right growth stage in right form and right placement, depending upon zone of feeder root concentration) strategy to economise both fertilizers and water use . Initial success on sensor-based sub-surface fertigation linking IOTs and machine learning, though has produced some encouraging results, but a long way in waiting before such developments are computerized at farm level from operation point of view.

Key words: Citrus, Irrigation, Fertilization, Water-use-efficiency, Nutrient-use efficiency, Fruit yield, Quality, Orchard longevity

Citrus (*Citrus* spp.) are cultivated between 40°N and 40°S, up to 1800 m altitude in the tropics and up to 750 m altitude in the subtropics. Citrus is the third largest grown fruit in India, originated in wet tropics in Southeast Asia, but large-scale commercial production is confined in the subtropics under irrigation (Srivastava *et al.*, 2000; Singh and Srivastava, 2004). The most commonly cultivated citrus species in India are : *Citrus reticulata* (mandarin), *C. sinensis* (sweet orange), *C. aurantifolia* (acid lime), *C. aurantium* (sour or Seville orange), *C. grandis* (pummelo, shaddock), *C. limon* (lemon), *C. medica* (citron), and *C. paradisi* (grapefruit). The optimum mean daily temperature for growth ranges between 23°C and 30°C, markedly reduced above 38°C and below 13°C. Active root growth occurs when soil temperatures are higher than 12 °C. Citrus is grown on soils that are sufficiently aerated and deep to allow tap roots to penetrate to the desired depths (1-2 m). Light to medium textured soils, free from stagnant water and sticky impervious layers are preferred (Srivastava and Singh, 2001a, 2008), avoiding the areas with high water table (Srivastava and Singh, 1997, 2002a) . Soil physical structure is of greater importance than the chemical properties, provided sufficient magnesium and minor elements such as zinc, copper and manganese are present in an available form, with soils with pH between 5.0 and 8.0 are preferred (Srivastava and Kohli, 1999 ; Srivastava and Singh, 2001b) .

Water as a basic component of plant cell tissue controls the growth and development of citrus trees through the water absorbed from the soil. Nutrients present in the soil are dissolved in water, taken up by the tree, and supplied to all parts of plant through translocation (Srivastava and Singh, 2004) . Hence, an adequate water supply during the growth stage has a significant influence on plant development, fruit quality and yield. In most citrus-growing areas, rainfall is unevenly distributed at different parts of the year, with marked dry and wet seasons (Srivastava and Singh, 2002b). To stabilize fruit production and quality, it is necessary to supply adequate irrigation in the dry season, and proper drainage during the wet season (Srivastava and Singh, 1999) in order to accomplish the water-use-efficiency and water productivity linking quality production of citrus. Therefore, it is important to provide the right amount of water and fertilizers at different growth stages not only enhance the growth of citrus trees, but also to improve the yield and fruit quality (Shirgure *et al.*, 2002a , 2002b). Amid these developments, recent studies (Meshram *et al.*, 2025a;2025b) highlighted the application of sensors in monitoring the irrigation and role of sub-surface fertigation on Indian Vertisols. In this background information , we attempted to take stock

Corresponding author : shirgure@gmail.com

of the developments that have taken place with regard to micro-irrigation and fertigation emphasizing citrus performance in both vegetative reproductive phases.

Vegetative Growth Citrus

Citrus species are small, evergreen shrubs or trees. In the subtropics, shoot growth occurs in a series of discrete flushes initiated by a rise air temperature (>12.5^{0}C) or, in the tropics, where the flushes are less discrete, by the availability of water (Davies and Albrigo, 1999). Seasonal variations in vegetative growth of Hamlin sweet orange in subtropical Brazil (22.5^{0}S) have been described by Ramos and Santos (2010), whilst the influence of water on growth and development of young trees is illustrated by experiments in Florida and Spain. Irrigation, at up to four-to-six day intervals in Hamlin sweet orange (*C. sinensis*) grafted on sour orange rootstock (*C. aurantium*) during first year after planting on a sandy soil, enhanced many components of vegetative growth, including leaf area, canopy volume and trunk cross-sectional area. (Marler and Davies, 1989). Similar results were obtained in Spain with eight-year-old Clementina de Nules mandarin trees (*C. Clementina* grafted on to Carrizo citrange rootstock) by Ginestar and Castel (1996). Withholding irrigation in the spring showed no effect on shoot extension in the first (spring) flush, but water stress in the summer (14 June to late-July /early-August) reduced shoot growth in second (summer) flush or even stopped in co-occurring. Water stress in the late-summer/early-autumn had a similar effect, but trees irrigated at this time, having previously been drought-affected, produced an abundant second (summer) flush composed mainly of flowers. The chronological studies are narrated as below :

- Shoot growth occurs in district flushed initiated by a rise in temperature (subtropics) or availability of water (tropics) (Jones *et al*., 1985).
- Water stress can delay the initiation of the summer and autumn flushes. Shoot and root growth alternate (Jones *et al.*, 1985; Bevington and Castle, 1985; Syvertsen and Llyod, 1994). Although, citrus cultivars are evergreen, leaves are shed throughout the year and continual leaf replacement occurs as the trees grow. The age at which a leaf drops is variable, but is usually between nine and 24 months leaves of all sizes are shed generally in the months immediately following blossoming (Kriedemann and Barrs, 1981).
- Canopy development and stem growth are both restricted by water stress (Kriedemann and Barrs, 1981).
- Water stress during periods of vigorous vegetative growth should be avoided (Doorenbos and Kassam, 1979). There is evidence of a direct causal link between stimulation of ethylene production by water stress and citrus leaf abscission (Kriedemann and Barrs, 1981).
- There is a poor correlation between trunk size and canopy development . Sun-exposed leaves represent only about 20% of the total leaf area of an orange tree canopy.
- The internal canopy does not receive more than 10% of the total photosynthetic photon flux density received at the canopy surface. Citrus leaves can reach temperatures of around 42^{0}C in the summer (Ribeiro and Machado, 2007).
- Excess vegetative growth can reduce fruit yields (Srivastava *et al*., 2000).

Flowering in Citrus

In Citrus. a stress period appears to be essential for flowering. The duration of the stress period determines the amount of flowers produced (Srivastava *et al.,* 2000) . The stress period, preferably of 1-2 months duration, can be induced either by low temperatures in winter (abut l0^{0}C) in the subtropics and in the tropics by a period of water deficit (monthly rainfall or irrigation 50 -60 mm). The flower-bud initiation occurs during this stress period when vegetative growth is minimum. Water deficits can have, however, some harmful effects for long-term crop production as compared to when dormancy is caused by a cold period. Once the stress period is ended, an adequate water supply is necessary because prolonged water deficits will not only delay flowering but also lead to over-production of flowers (Srivastava and Singh, 2008). This can result in lower yields during the next season and possibly in subsequent seasons to a biennial fruit-bearing cycle. For lemons, water deficits in summer are commonly used to start off-season flowering for year-round production. The flowering period is very sensitive to water deficits. Water deficits directly reduce fruit set; also during this period nutrition, especially nitrogen, is essential and adequate water is necessary to make the nutrients available to the crop. Moreover, water deficit during fruit setting reduces yield by causing a heavy June or December fruit drop (Srivastava *et al*., 2003).

Iglesias *et al.* (2010) have recently published an overview on the physiology of flowering and fruiting in Citrus. According to this report, it takes two- to -five years from planning for a citrus tree to reach a stage when it can produce flowers. In subtropical areas, flowering takes place after a period of bud quiescence as a result of exposure to low temperature in winter. In the tropics and in areas with a dry season, rehydration after a period of water stress triggers the flowering process. The inflorescence may be leafless flower-bud only or leafy (vegetative and flower bud both present on the same shoot) the degree of fruit setting is dependent on the type of inflorescences formed. In general, leafless inflorescences emerge first and contain a bouquet of flowers with a low likelihood of setting fruit (Srivastava *et al.*, 2000). By contrast, flowers in leafy inflorescences are commonly associated with a better fruit setting (the fewer the number of flowers on a stem the higher the proportion that form fruits). In seeded cultivars, pollination (mainly by bees) and fertilization are necessary to initiate fruit development, but not in the seedless cultivars (mainly by bees), fertilization is necessary to initiate fruit development (Iglesias *et al.,* 2010). The practical aspects of evaluating the intensity of flowering in citrus has been studied by Ribeiro *et al.* (2008). Citrus trees bloom profusely (e.g. for sweet orange as many as 2,50, 000 flowers /tree can be formed). This number is considerably reduced by the abscission of flower buds , with some important studies as highlighted as below:

- Rest period is necessary for induction of flowering to take place, can be provided by low temperature in the subtropics or by drought in tropics. Too much stress can result in the production of too many flowers, may lead to biennial bearing (Doorenbos and Kassam, 1979 ; Srivastava *et al.*, 2000).
- Rain/irrigation after drought induces flowering, undesirable in midseason (Smajstrla, 1993). In some parts of the subtropics, the 'rest period' is induced by two successive months with mean air temperatures, presumably at 10^0C or less and in the tropics by water stress (monthly rainfall less than 50-60 mm).
- Allowing a water deficit to occur in the summer is commonly used to initiate flowering for year-round fruit production in lemons (Doorenbos and Kassam, 1979).
- Water stress during flowering increases shedding of flower buds and flowers before fruit is set. These effects are due to weakening of the (two) pre-formed abscission zones at the points of attachment (Jones *et al.*, 1985).
- Water stress during the fruit expansion phase affects final fruit size (but can increase the content of the total soluble solids (TSS) and acids) (Doorenbos and Kassam, 1979).

Crop Water Requirement

Citrus trees are evergreens and thus transpire throughout the year. Water requirement for high production vary with climate, ground cover, clean cultivation or no weed control, species and rootstock. The water requirements for grapefruit are somewhat higher than for the other citrus species, with total water requirements varying between 900 and 1200 mm per year (Srivastava and Singh, 2008). As a perennial crop the response of citrus to water supply at a particular period of development will depend greatly on the level of water supply prior to that period during the same growing season and also the level of water supply during previous growing seasons. New vegetative growth in any year is influenced by residual effects of growth in previous seasons. The vegetative growth of young trees determines their final tree size and future fruit-bearing capacity (Srivastava and Singh, 2001b). While, for mature trees, the growth vigour determines the replacement rate of fruit-bearing branches. Any effect of water deficit on root and leaf development may impair the number and size of fruits later in the season. Water deficits must be avoided when vegetative growth is most rapid. Prior to flowering and fruit setting, however, too vigorous, luxurious growth may impair production of high quality fruit (Shirgure *et al.*, 2003a, 2003b, 2004).

The water-balance method was used by Garcia Petillo and Castel (2007) in southern Uruguay (34^0 39'S 56^0 46' W; alt. 30 m), in a three-year-period, to measure the actual water use (ET) by mature orange trees (*C. sinensis* cv. Valencia) grafted on the trifoliate rootstock (*C. trifoliata*). In a carefully monitored trial, annual water used averaged 767 mm from drip-irrigated trees and 620 mm from rain-fed trees spaced 6 x 4 m with 416 trees ha^{-1} (crop cover increased from 30 to 50% during the course of the experiment). Seasonal potential evapo-transpiration rates (ETc) increased from 1.3 mm d^{-1} in the winter to 2.8 mm d^{-1} (spring) to 3.0 mm d^{-1} (summer) before declining to 1.0 mm d^{-1} in the autumn. These values are similar to those recorded in Florida, Valencia (Spain) and in less and areas of Israel, but less than those reported from Texas, Arizona, South Africa and Iran (Garcia Petillo and Castel, 2007), where reference-crop evapo-transpiration rates (ET_0) were estimated from a USWB Class A evaporation pan with an appropriate pan factor (Allen *et al.,*1998).

In southern Brazil, Marin and Angelocci (2011) monitored the water use of seven-year-old irrigated (with under-tree micro-sprinklers) acid lime trees (*C. latifolia,* grafted on to *C. limonia* rootstock) over a (dry) winter and a (wet) summer season. In dry year, including cold/ frost protection) were within the SFWMD permitted levels (300-560 mm, which excluded irrigation for cold protection), and that the simulated estimates were generally less than the values for individual districts, which in turn were reasonable. Similarly, Wheaton *et al.* (2006) used a water- balance approach to simulate the effects of a selection of variables. In particular the 'allowable' depletion of available water at different growth stages, on the annual irrigation requirements of a Hamlin orange orchard (*C. sinensis* grafted on to *Carrizo citrange* rootstock) planted on a free draining sandy soil in Lake county, Florida (USA).

Table 1: Crop water requirements and Kc of Citrus cultivars. (ET_o is the reference crop evapotranspiration, ETc is the potential evapotranspiration from a citrus orchard and Kc is the crop coefficient (K_c=ET_c/ET_o). T is transpiration. '?' means value uncertain. (units in mm d^{-1})

Parameter	Spring	Summer	Autumn	Winter
Uruguay (orange)[a]				
ET_o	3.5	5.0	1.3	1.5
ET_c	2.8	3.0	1.0	1.3
K_c	0.80	0.60	0.77	0.87
Brazil (lime)[b]				
ET_o	-	4.5	-	2.5
ET_c		2.5		0.6
K_c	-	0.65?	-	0.24
Italy (clementine)[c]				
ET_c	-	6-8	-	
K_c	1.0-1.2	Up to 1.2	0.8	
Spain (clementine)[d]				
ET_c	2.1		2.6	
K_c	0.43		0.44	
T/ET_o	0.25		0.30	

Source : Marin and Angelocci (2011), Rana *et al.* (2005), Villalobos *et al.* (2009)

Quantifying water requirements of an orchard crop like citrus is not that easy to compare the results of measurements taken under different conditions and with different methods. However, it appears to be accepted that low stomatal/canopy conductance restricts water use of Citrus spp. compared with other crops. Recently reported research, summarized in Table 1 indicated that potential water use (ET) by mature orange trees in the subtropics ranges from 1.0 (autumn) to 3.0 mm d^{-1} (summer, maximum ET_c = 3.3 mm d^{-1}, which is equivalent to 80 litres/ tree/ day).

The corresponding K_c values are 0.77 (autumn) and 0.60 (summer). For seven-year-old lime trees in Brazil, ET_c (summer) = 2.5 mm d^{-1} (Kc = 0.65) and ET_c (winter) = 0.6 mm d^{-1} (Kc=0.24, a low value due to dry inter-row vegetation). In contrast, ET_c rates for clementine reached 6-8 mm d^{-1} in Italy with a correspondingly high crop coefficient (up to 1.2). In Spain, the equivalent kc values were much lower at c. 0.4. For comparison, Kridemann and Barrs (1981) had earlier cited values for (the equivalent ot) K_c=0.7 (summer) and 0.6 (autumn) in south Australia, as well as seasonal K_c mean values of 0.83 (in Arizona) and 0.68 (in Israel). Given the variability in some of the results reported, and until more is known about citrus water requirements, the approach proposed by Allen *et al.* (1998) seems reasonable.

Irrigation Scheduling in Citrus

Basically, citrus trees do not exhibit visible symptoms of water stress until most of the available soil moisture has been depleted. Consequently, extensive research in the citrus production areas has led to the recommendation that water be applied at one-third depletion during January through June and at two-thirds depletion over the remainder of the year. Irrigation scheduling requires great caution. Citrus trees demand good soil aeration and over-irrigation is highly detrimental, particularly to young trees. Too frequent and heavy irrigations may affect root development and yield and lead to leaching of nutrients. In recent years, a diversity of methods has been used to measure the actual water use of Citrus. These methods include the water-balance approach (with orange) in subtropical southern Uruguay, and the aerodynamic method in Brazil (lime), Italy (clementine) and Spain (clementine). The sap-flow technique has been used to estimate transpiration in Brazil and Italy. Evaporation modeling with multiple linear regression as well as artificial neural network was studied for citrus crops (Shirgure *et al.*, 2001a, 2001b, 2001c, 2001d).

Depletion of available soil moisture can be measured indirectly as a mathematical computation which correlates Class "A" pan evaporation data with evapotranspiration (ET_o). Given that citrus requires about 45 to 50 inches of water annually, evapo-transpiration models that are based on 60-80% of pan evaporation (the crop coefficient, as it is called) indicated a close correlation with total amount of water. However, classic work in citrus growing parts of the USA, predicted citrus water use with actual use as measured by neutron probe, revealed that the models were fairly accurate in spring and fall months, but overestimated the amounts needed in winter and underestimated the amounts needed in the summer. When these findings were applied to conditions in India, it was determined that the citrus coefficient should be adjusted for the winter and the summer periods. The irrigation scheduling and microirrigation systems were also studied in Nagpur mandarin (Shirgure *et al.,* 2004d, 2014; Shirgure and Srivastava, 2014a). The Kc values for different growth stages with no vegetative ground cover is further highlighted (Table 2).

As early as Hashemi and Gerber (1967) attempted correlation between actual evapo-transpiration and potential evapo-transpiration computed with Penman's model. Koo (1968) advised Florida citrus growers to maintain soil moisture at 55 to 65% of field capacity from bloom the young fruit exceeds 1 inch in diameter. Retiz (1968) estimated the water requirement of citrus at 40-45 inch/year. Richards and Warnke (1968) studied

Table 2: Stage- wise crop coefficients used for irrigation water management in Nagpur mandarin

Crop characteristic	Stages of Development				
	Initial	Crop development	Mid-season	Late	Total
Stage length, days	60	90	120	95	365
Depletion Coefficient, p	-	-	-	-	0.5
Root Depth, m	-	-	-	-	1.2
Crop Coefficient, Kc Citrus with ground cover					
70 % canopy	0.7	>>	0.65	0.70	-
50 % canopy	0.65	>>	0.60	0.65	-
20 % canopy	0.5	>>	0.45	0.55	-
Yield Response Factor, Ky	-	-	-	-	0.8-1.1

Source: Shirgure and Srivastava (2014b)

the irrigation systems to lemon and irrigation at 60 centibar(cb) and extrapolations to 150 cb resulted in no measured differential response in tree growth and fruit yield under coastal conditions. Leyden (1977) reported that 610 mm irrigation water applied via a drip system at 0, 200, 300 and 400 liters/tree gave the significant difference in total yield and fruit size distribution. Toledo (1980) showed that irrigation at 65% field capacity caused drought injury symptoms, excessive defoliation, less water consumption. Best results were obtained with irrigation at 85% filed capacity. Evapotranspiration ranged from 3.78 to 4.42 mm/day and 1.46 to 1.3 mm/day for 85% and 65% field capacity irrigation, respectively. Kelin (1983) compared drip irrigation scheduling according to soil water potential to class A pan evaporation in different horticultural crops using a crop factor and concluded that 12-23% water could be conserved by using the irrigation scheduling based on soil water potentials.

Moreshet *et al.* (1988) compared the 100% and 40% of soil volume irrigation in '*Shamouti*' orange and found that partially irrigated plot was 66% of the fully irrigated one. Transpiration from the trees of partially irrigated plots was 72% of that of the fully irrigated plot and evaporation from soil surface was 58%. Fruit TSS and acid contents were higher in partially irrigated plots. Smajstrala *et al.* (1986) found that greatest yield was obtained using spray-jet trickle irrigation. Yield increases were not linear with volume of root zone irrigated but ranged from 39% for the drip irrigation treatments which irrigated 5-10% of the area beneath the tree canopies to 64% for 2-spray jet per tree, which irrigated 50.7% of the areas beneath the tree canopies. Du Plessis (1985) obtained the highest yields (190 kg/tree) and the largest average fruit size with irrigation at a crop factor of 0.9 on a 3-day cycle, with thin consumption micro-irrigation gave better results than drip irrigation. Smajstrala *et al.* (1986) and Shirgure *et al.* (2001c, 2001d) concluded that the tree growth of young Valencia orange was greatest when irrigations were scheduled at 20 cb for no-grass and 40 cb for the grass treatments. Barbera and Carimin (1986) studied different levels of water stress on yield and quality of lemon tree and found that yield was lower in most stressed plot. The number of flowers/m^3 of canopy was higher in most stressed treatment, indicating a relationship between severity of stress and flowering response. The daily water requirement of bearing Nagpur mandarin and acid lime is further estimated (Table 3).

Du Plessis (1985) with a mature 'Valencia' orange trees and field experiment showed that water use pattern over the entire season reaching a maximum of 87 liters/day$^-$ in January, with 690 liters irrigation when tensiometer reaching fell to -50kpa gave the highest net income. Use

Table 3 : Daily water requirement of Nagpur mandarin acid lime (Liters /day/ tree)

Month	Young tree (20 % ground cover)		Middle grown tree (50 % ground cover)		Mature tree (70 % ground Cover)	
	Nagpur mandarin	Acid lime	Nagpur mandarin	Acid lime	Nagpur mandarin	Acid lime
January	14.96	10.96	44.22	40.22	71.44	67.44
February	20.15	16.15	59.40	53.40	96.18	91.18
March	26.17	21.17	78.48	74.48	126.50	122.50
April	29.16	25.16	87.48	83.48	142.88	138.88
May	33.98	30.98	101.94	97.94	165.91	155.91
June	21.73	20.73	66.42	57.42	109.89	92.89
July	18.27	14.27	55.80	51.80	92.38	88.38
August	13.95	11.95	42.45	38.45	70.25	64.25
September	14.96	10.96	45.63	41.63	75.49	69.49
October	16.87	12.87	51.56	48.56	91.90	71.90
November	14.97	11.97	44.88	40.88	73.80	68.80
December	11.25	8.25	34.88	29.88	56.97	52.97

Source: Shirgure *et al.* (2002b , 2003b , 2004a) of tensiometer rather than evaporation pan scheduling could save 2000 m^3 water/ha annually. Sanehez Blenco *et al.* (1989) compared five flood irrigation treatments with daily drip irrigation at 0.475 Epan and concluded that drip irrigation gave higher yields as compared to flood irrigated plants. Castel and Buj (1990) carried out trials on mature Satstuma average trees grafted on sour orange rootstocks. Plants were irrigated with 60% of the estimated ET losses from a class A-pan and 80% of the control throughout the year.

The preliminary studies on the effect of soil management system on soil moisture in Sweet orange orchard was initiated by Randhawa *et al.* (1960). He also emphasized on irrigation aspects in citriculture in India. Makhija *et al.* (1986) obtained water need for 6- year-old Kinnow mandarin varying from 539 to 1276 mm depending upon the level of irrigation with average consumptive use of water in 2 years as 61.5 cm. Mageed *et al.* (1988) carried the research on influence of irrigation and nitrogen on water use and growth of Kinnow mandarin receiving 4 levels of irrigation and three levels of nitrogen (0,115 or 230 kg N/tree). The consumptive use varied from 66.7 cm to132.5 cm. Ghadekar *et al.* (1989) estimated that the consumptive use of Nagpur mandarin by modified Penman equation using 40 years air temperature, Relative humidity, wind velocity and Solar relation data. Under clean cultivation the water requirement of young, middle age and mature trees was observed as 651.9, 849.0 and 997.3 mm/year, respectively. An equation for daily water use was proposed and it can be used for drip irrigation. Ray and Sharma (1990) studied the response of young Kinnow mandarin to irrigation. Irrigation was scheduled at -0.05, -0.1, -0.2, -0.4 and -0.8 MPa soil water potential 0.8 IW/CPE ratio and irrigation to replenish estimated crop ET. The highest bio-mass per plant was obtained when irrigation was scheduled at -0.05 MPa SWP and 18-19 irrigations were required.

Shirgure *et al.* (2000, 2004a, 2004b, 2004c) initiated the irrigation scheduling based on depletion of available water content and fraction of open pan evaporation in acid lime in pre-bearing stage. Studies were also done to see the effect of different soil moisture regimes with irrigation scheduling based on available soil moisture depletion and open pan evaporation on soil moisture distribution and evapotranspiration in acid lime. He concluded that evapotranspiration varied from 213.6 mm to 875.6 mm in various irrigation schedules. It was also found that the change in soil moisture distribution in the root zone of acid lime plants varied from 195.9 mm to 321.3 mm with different irrigation schedules (Shirgure and Srivastava , 2014a, 2014b , 2014c).

Irrigation Methods in Citrus

The common methods of applying water to orchards are basin, border strip, furrow, sprinkler and drip irrigation. Ring basin is generally followed in early establishment phase of fruit trees. Microirrigation to citrus is common in developed countries (Singh and Srivastava, 2004). Drip and microjet irrigation has advantage over surface irrigation methods, for more uniform and complete wetting of the soil surface and adoption on sloppy terrain. The most common surface irrigation methods are furrow irrigation (several furrows between the tree rows), check irrigation (basins containing one or more trees) or flood irrigation (where citrus trees are planted on beds or ridges). Because of uneven water distribution and difficulty of applying small amounts of water the importance of surface irrigation for citrus is decreasing. Sprinkler irrigation may provide a more uniform distribution of water and the possibility of applying exact depth of required water (Shirgure and Srivastava, 2014, 2015). With the drip or micro-jet systems, water savings may be obtained because water is applied only to root zone, leaving the remaining part of soil dry. Sprinkler irrigation is also frequently used for frost protection.

Faton (1970) observed better tree growth and yield, less weed growth, evaporation and leaching with 16 gallons water applied through drip to each 4-years old lime trees at two weeks interval compared to 320gallon water in flood irrigation. Fritz (1970) observed that all applied water is transferred directly to root zone of plants and 20-50 % water saving is reported depending on soil and climate. Raciti and Sckderi (1977) compared drip irrigation with basin and found that the fruits under drip system ware more acidic with lower maturity ratio. Ronday *et al.* (1977) observed better tree growth and less water consumption in 'Valencia' orange under drip irrigation in sandy soil. Sucderi and Raciti (1978) compared basin irrigation with different combination of drip irrigation and measured number, weight, quality of fruits in Valencia orange. Slack *et al.* (1978) demonstrated that trickle irrigation on young orange trees used 5,400 liters of water compared to 23,400 liters of water per tree for dragline.

Microirrigation Systems

With proper design and operation, drip systems provide adequate soil moisture for optimal growth and production while using only about 12-15 inches of water/ acre/ year. Such savings result from better water use efficiency, negligible evaporation and deep percolation losses, and water is applied to only a limited soil surface area, under which the absorptive root system of the tree is concentrated (Shirgure *et al.,* 2001c, 2001d). However, one drawback to drip irrigation in India with regard to citrus is that in years of adequate rainfall, the roots grow far beyond the drip-irrigated zone of soil. However, such roots necessarily die during subsequent extended dry spells such as have occurred several times over the last few years. The other drawback is that drip systems provide no cold protection for the orchard. Some growers operate the system too long thereby water logging the wetted zone where the roots are concentrated and pushing water too deeply into the soil profile. Regardless of the type of irrigation system and other production inputs, final productivity, fruit size and fruit quality can only be as good as the management of supplemental irrigation in the citrus orchard. The automatic drip irrigation scheduling using hybrid station controller is studied in Nagpur mandarin (Shirgure and Srivastava, 2014, 2015). Raciti and Barbargallo (1982) reported that the yields of lemon was more with localized irrigation amounting to 227.23 q/ha and 213.2 q/ha for basin irrigation. Ozsan *et al.* (1983) compared furrow, under tree, over tree and drip irrigation in lemons. amounts of water applied were greatest (1286 mm) with under-tree method and least (207 mm) with drip irrigation system. Yield was more with over tree sprinkling and least with furrow.

Water-use-efficiency was high in drip irrigation. Cevik and Yazar (1985;1987) demonstrated that a new irrigation system, i.e. Bubbler irrigation for the orchards. He observed that under tree sprinkling and drip irrigation had the best pomological effects. Amounts of water applied per tree for over sprinkling, under sprinkling and drip irrigation were observed as 22.01, 17.04 and 10.33 m^3/season, respectively . Capra and Nicosia (1987) studied flooding, sprinkler, and sub-irrigation with sprays and concluded that the rates of water application affects the rate of growth of fruit diameter. Robinson and Alberts (1983) compared under canopy sprinkler and drip irrigation systems in crop like banana and found that the drip irrigation is superior to under canopy sprinklers. Increased tree growth and yield were recorded in young Valencia orange under drip irrigation method with emitter placed at distance of 1 meter from the trunk (Azzena, *et al.,* 1988). Greive (1988) concluded that under tree micro-sprinklers increased yield by 12% and reduced water application by 9.3% compared to conventional full ground cover. Intrigliolo and Raciti (1989) demonstrated that water saving with sub-surface irrigation was 32% over the traditional basin irrigation. The yield was higher but fruit quality was not much different. Marler and Davies (1989;1990) studied the effect of micro-sprinkler irrigation scheduling on growth of young 'Hamlin' orange trees and found that growth was not affected by pattern of irrigation, suggesting that 90% emitters are enough for root system. Zekri and Parsons (1989) studied drip, micro-sprinkler and overhead sprinkler irrigation at two water application rate and found that fruit size and tree canopy area were 9 -20% greater in the overhead sprinkler treatments.

Citrus orchards can be irrigated in many different ways. For example, In Florida, solid-set sprinkler systems, rainguns, flood and subsurface methods have all been used. Specific types of micro- irrigation systems include drip (trickle) and micro- sprinklers (under- tree) these systems allow small quantities of water to be applied at frequent intervals, usually to only part of the root zone. In Swaziland, largely because of the opportunities it offers for labor saving, water saving and power saving, micro- irrigation (particularly drip) has replaced under-tree drag- line sprinkler systems (Pyle, 1985). In areas prone to frosts (e.g. Florida), micro- sprinklers can also provide some protection against frost damage to young trees (Rieger *et al.,* 1986). of nutrients in soluble form, together with water, directly into the root zone. Good irrigation management is necessary to minimise leaching of nutrients. Shirgure *et al.* (2001d) initiated the research work on evaluation of microirrigation systems in acid lime and a comparison was done with that of basin (ring) method of irrigation. Shirgure *et al.* (2003a) studied the effect of dripper 8 Lph, micro-jet 300^0, micro-jet 180^0 and basin irrigation method on water use and growth of acid lime and found that micro-jet 300^0 recorded higher growth than rest of the systems. The studies on the efficacy of these micro-irrigation systems and basin irrigation on fruit quality and soil fertility changes in bearing acid lime revealed that the micro-irrigation systems and that too micro-jets are best suited for the sustainable production of good quality acid lime (Shirgure *et al.,* 2002b, 2003a, 2003b).

An advanced form of this method of irrigation was developed in Spain and has since been commercialized in several countries, including Australia, South Africa and the USA. Known as open hydroponics, citrus trees are planted at a high density (> 750 trees/ ha) and irrigated (with drip) by short- duration, low- volume pulses throughout daylight hours with fertilizer injected into the water (expect on rainy days). In this way, water and nutrients are readily available within the wetted soil volume, where a mat of roots develop (Falivene, 2005). After two years' commercial experience in Florida with what is called the advanced citrus production system, the observed benefits included early production of high-quality fruit (at 24 months) with the opportunity to achieve potential yields when the trees mature. As there is a limited reserve of available water in the (restricted) root zone, especially in sandy soils, the system is vulnerable to breakdowns.

Good management is essential. Looking to the future, there are opportunities to extend the system to very high - density citrus production under cover. Microjet or micro-sprinkler irrigation systems utilize only one emitter per tree, usually situated on a riser or stake to hold the emitter upright in place. Emitters are available with outputs of 16 -100 liters or more per hour. Most will wet an area up to 7-8 feet from the emitter, thereby producing a wetted surface area equal to or slightly greater than the canopy area of a mature tree (Shirgure *et al.,* 2000 , 2001c , 2004c).

Fertigation in Citrus

Fertigation, the application of soluble fertilizers through micro-irrigation systems, has been used in citrus production since the 1960s. Originally, fertigation was used in arid regions to improve solubility of fertilizers in the root zone and increase uptake efficiently by fruit trees. Without rainfall or irrigation, dry fertilizers often remained on the soil surface and nutrients were lost due to leaching or volatilization. Currently fertigation is being used in many citrus growing regions including Israel, the Mediterranean region, South Africa, and the United States. Nevertheless, many regions in our country still use dry fertilizers due to tradition, lack of fertigation equipment, technique, uneven topography or poor quality irrigation water (Panigrahi and Srivastava , 2017). In humid regions with high rainfall, roots are more widely distributed over the orchard floor and the root concentrating effect of fertigation is less pronounced (Shirgure *et al.,* 2004d,; 2014). Fertigation systems are easily automated and provide an effective delivery system for water and fertilizer. Once the tanks, injectors and back flow valves have been purchased and the irrigation is in place, many citrus trees can be fertigated at the touch of a switch. A wide range of application frequencies are available, ranging from daily to monthly, and can be adjusted easily without additional costs for fertilizer spreaders or labor. A properly maintained and managed fertigation system in addition is an effective means of irrigating. Thus, citrus tree water relations are also often improved when using fertigation.

Fertigation response in citrus

The influence of fertigation on growth, yields and fruit quality of citrus trees has been studied for more than 30 years, with differing, sometimes contradictory findings. Results differ based on climate, soil type, root distribution and possibly tree age. Fertigation is an effective method of fertilizing in arid climates such as Israel (Dasberg *et al*., 1983; Jeyabaskaran *et al*., 2021). Fertilizer levels in soil are maintained at constant levels of 35-60 mg/kg throughout the irrigation period. Studies suggest that optimum nitrogen rate for mature Shamouti orange trees is about 170 kg $ha^{-1}year^{-1}$. Higher nitrogen (N) rates increased yields but decreased external fruit quality by delaying peel colour development and increasing peel thickness. However, juice quality, specifically total soluble solids, was not affected by nitrogen rate. The reduction in fresh fruit quality and increased costs for the additional nitrogen were probably not economically warranted. Similarly, research from Spain with navel oranges showed that daily fertigation significantly increased yields over application of dry fertilizer twice/year (Legaz *et al*., 1981). Optimum nitrogen rate was 0.75 kg $tree^{-1}yr^{-1}$.

High N rates increased fruit weight and number but also increased peel thickness and decreased juice content. In this instance, fertilizer was applied using 8 $dripperstree^{-1}$ to insured adequate root zone coverage that is an important factor in any fertigation program. Fertigation does not always increase tree growth and yields over application of dry materials. Therefore, general recommendations concerning its effects cannot be made. Studies from South Africa found no difference in growth of young Valencia orange trees during the first 4 years after planting when using fertigation (6 times $year^{-1}$) vs. dry application (4 times per year) at the same nitrogen rates (Bester *et al*., 1977). Fertigation effects on tree performance are even less pronounced in humid subtropical areas such as Florida and Texas. In contrast to Spanish and Israeli findings, growth of 1-2 year-old ′Hamlin′ orange trees was similar for fertigated and dry applications over a range of nitrogen rates (Willis *et al*.,1990).

The research related to injection of fertilizers through the drip irrigation systems was started by Smith *et al.* (1979). Koo (1981) appraised the potential advantage of micro-irrigation systems and its usefulness to fertigation. Bielorai *et al.* (1984) advocated use of fertigation technology in citrus as it resulted in higher production of good quality Shamouti oranges, comparing N fertigation at 100, 170 and 310 kg/ha with broadcast application at 170 kg/ha through irrigation system. Average yields for 4-years were recorded as 62, 73 and 82 tons/ha with 100, 170 and 310 kg N/ha, through fertigation. Koo and Smajstrala (1984) supplied 15% and 30% of crop N and K requirements through fertigation and rest through conventional method to Valencia orange. Partial fertigation of N and K resulted in lower N contents of leaves. TSS and acid concentration in juice was also reduced but yield was not affected. Haynes (1985) discussed the principles of fertilizer use for trickle irrigated crops. Haynes (1986) also studied the comparison of fertigation with broadcast applications of urea on levels of available soil nutrients and on growth and yield of trickle irrigated peppers. He found that growth and yields were greatest at the low rate of N applied as fertigation or as a combination of broadcast plus fertigation.

Fouche and Bester (1990) tried various fertilizer combinations through fertigation on 13-year-old Navel oranges. Fertigation was given with a soluble fertilizer 'Triosol' (3:1:5) + 350 gm urea by broadcast, fertigation of N and K with broadcast of single super phosphate and NPK through broadcast. Highest yields was obtained with fertigation of NPK through Triosol or by complete broadcasting of NPK fertilizers. No significant differences were observed as fruit size, acidity, percent juice content and TSS among treatments. Beridze (1987) conducted a rial on 5- year- old lemon tree and fertilized 150 kg N + 120 Kg P_2O_5 + 90 Kg K_2O/ha as basal dressing. The highest yield of 6.6 ton/ha was obtained from trees fertilized with basal dressing + 250 Kg peat/tree as a mulch + FYM at 25 tons/ha. Ferguson *et al.* (1990) studied the fertigation as growth of 'Sunburst' tangerine trees. Two years old *C. reticulata x C. paradisi* cv. Sunburst was fertilized with 0.66 or 1.32 lb N/tree during 1988-89 and it was 0.52 or 1.05 lb N/tree during 1990. Leaf analysis showed that low to deficient concentrations of N, K, Mn and Zn with both N treatments. Zekri and Koo (1994) tried micronutrients through fertigation with different sources of various rates. Inorganic forms (NO_3 and SO_4) were ineffective in evaluating micro element levels in oranges. But, chelated sources of Fe, Mn, Zn and Cu were very effective and their rates of application were comparable with rates through foliar applications.

Neilsen *et al.* (1993) studied that fertigation with calcium ammonium nitrate showed increased vigour and leaf Ca concentration but decreased leaf Mg and Mn compared to trees fertigated with urea or ammonium nitrate (NH_4NO_3) in apple trees. Fertigation with P increased early tree vigour, leaf and fruit P concentration and decreased leaf Mn. Syvertsen and Smith (1996) studied the nitrogen uptake efficiency and leaching losses from Lysimeter grown trees fertilized at three nitrogen rates. He concluded that Average N uptake efficiency decreased with increased N application rates, overall canopy volume and leaf N concentration increased with N rate, but there was no effect of N rate on fibrous root dry weight.

Irrigation at 20 % depletion of available water content and fertilizer treatment of 500 g N + 140 g P_2O_5 + 70 g K_2O/ tree individually were observed to be optimum irrigation and fertilizer requirement, respectively. Combined application of these two treatments produced significantly higher magnitude of fruit yield m^{-3} of canopy in addition to higher N, P and K status, and other fruit quality indices (Shirgure *et al.* 2004d; Srivastava *et al.,* 2003). The fruit yield (26.1 kg/tree), fruit weight (135.1 g), total soluble solids in fruits and juice percentage (47.32%) were higher with irrigation scheduled at 20 % and 500N-140P_20_5-70K_2O gplant^{-1} fertigation (Shirgure *et al.,* 2001c). The incremental height (0.40 - 0.60 m), stock girth (4.07 - 4.26 cm) and canopy volume (6.93 m^3) of bearing acid lime was more in irrigation scheduled at 30% depletion of available water content with 500:140:70 fertigation. The combined effect of irrigation at 30 % depletion of available water content and fertigation with 500N:140 P_20_5:70 K_2Og/ tree gave better growth and yield of acid lime. The juice percent and acidity with irrigation scheduled at 30 % depletion of available water content and 500:140:70 fertigation was more (42.5% and 7.0%) as compared to other treatments (Shirgure *et al.*, 2004c, 2004d), with developed fertigation schedule for Nagpur mandarin further highlighted (Table 4). The highest TSS/acidity ratio was observed with K fertigation with 40 g K_2O/plant at 30-days interval (10.0).

Table 4: Fertigation schedule for Nagpur mandarin crop (Spring bloom) grown on deep black soils of central India

Month	N g/plant	P_2O_5 g/plant	K_2O g/plant	$ZnSO_4$ g/plant	$FeSO_4$ g/plant	$MnSO_4$ g/plant	Borax g/plant
October	60	-	-	-	-	-	-
November	60	-	-	-	-	-	-
December	Stress period						
January	60	30	15	50	50	50	25
February	60	30	15	50	50	50	25
March	60	30	15	50	50	50	25
April	60	30	15	50	50	50	25
May	60	30	15	-	-	-	-
June	60	30	15	-	-	-	-
Jul-Sept	-	-	-	-	-	-	-
Total	480	180	90	200	200	200	100

* Fertigation dose for bearing Nagpur mandarin is 480N:180P_2O_5:90K_2O g/tree/year
* Urea phosphate (18:44:0), urea (46:0:0) and potassium nitrate (13:0:46) were used to meet nutrient requirement
*No fertigation schedule adopted in July-Sept due to rains.
Source : Shirgure *et al.* (2014a)

Fertigation with 40 g K_2O/plant at 30-days interval using sulphate of potash fertilizer through micro-irrigation proved to be very effective for better fruit yield and quality of Nagpur mandarin (Shirgure and Srivastava, 2013b). Therefore, use of micro-irrigation and K- fertigation technique will be a sustainable solution for increasing the productivity as well as fruit quality of Nagpur mandarin orchards (Shirgure and Srivastava, 2013a , 2013b).

CONCLUSION AND FUTURE STRATEGIES

Citrus is hence perceived as highly water-responsive fruit tree crop. Despite many breakthroughs in microirrigation and fertigation , their adaptability in citrus orchards, especially under changing climate (Barlas and Srivastava, 2026; Srivastava *et al.*, 2026) is still below the satisfaction, thereby jeopardizing the progress gained in these accomplishments. No doubt , the area under microirrigation is consistently on rise, especially under fruit trees with citrus no exception. By a simple guesstimate, quality yield has been observed to improve by 25-30% with saving on chemical fertilizers by 30-35% over conventionally used basin irrigation coupled with basal method of fertilizer application. The future strategies need to be addressed in terms of : i.development of sub-surface micro-irrigation systems for better water use in citrus along with macro and micro-nutrient fertigation in citrus cultivars; ii.automation for the micro-irrigation system as well as fertigation system in citrus; iii.irrigation scheduling with infrared thermometry and crop water stress index; iv. citriculture under regulated deficit irrigation and pulse irrigation systems as well as partial root wetting concepts under high-density planting; v. artificial intelligence and machine learning-based irrigation management and requirement of nutrient types as per crop phenology as a part of fertigation .

REFERENCES

Allen R G, Pereira L S, Raes D and Smith M 1998. Crop evapo-transpiration-Guidelines for computing crop water requirements. I*rriagation and Drainage Paper* 56, UN Food and Agriculture Organisation, Rome, Italy.

Azzena M, Deidda P and Dettori P 1988. Drip and micro-sprinkler irrigation for young Valencia orange trees. *Proc. Sixth Intern. Citrus Cong. Tel Aviv, Israel* **2**: 747-51.

Barbera G and Carimin F 1988. Effect of different levels of water stress an yield and quality of lemon tree. Sixth Intern. *Citrus Cong. Tel Aviv Isreal* **2**: 717- 22.

Barlas N T and Srivastava A K 2026. Citrus nutrition under changing climate: Bibliometric insights and trends. *Journal of Plant Nutrition* **49**(9):1664-89.

Beridze T R 1990. The effect of organic fertilizers on lemon tree productivity. *Sub tropicheskie Kul'tury* **3:** 83-86.

Bevington K B and Castle W S 1985. Annual root growth pattern of young citrus trees in relation to shoot growth, soil temperature, and soil water content. *Journal of American Society of Horticultural Science* **110**(6):840-45

Bester D H , Foriche P S and Veldman G H 1977. Fertilizing through drip irrigation systems on orange trees. *Proceedings of International Society of Citriculture* **1**:46-49.

Bielorai H , Erner D and Brum M 1984. The effect of fertigation and partial wetting of the rootzone on production of Shamouti orange. *Proceedings of International Society of Citriculture* **1**: 118-20.

Capra A and Nicosia OUD 1987. Irrigation management in citrus orchards. *Irrigazine* **34**(1):3-15.

Castel J R and Buj A 1990. Response of Satustinana oranges to high frequency deficit irrigation. *Irrigation Science* **11** (20) : 121-27.

Cevik B and Yazar A 1985. A new irrigation systems for orchards (bubbler irrig.). *Doga Bilim Dergisi* **9(**3): 419-24.

Cevik B and Yazar A 1987. Studies for determining the most efficient irrigation method for growing lemons under Cukurova conditions. *Doga, Tarum ve, Ormaniciuk* **11**(1): 42-43.

Dasberg S, Bielorai H and Erner J 1983. Nitrogen fertigation of Shamouti oranges. *Plant and Soil* **75**:41-49.

Davies, F S and Albrigo L G 1994. Citrus Oxon, CAB International.,USA.pp.38-56.

Doorenbos J and Kassam A H 1979. *Yield Response to water.* Irrigation and Drainage Paper 33, UN Food and Agriculture Organisation. Rome, Italy.

Du Plessis S F 1985. Irrigation of citrus. *Citrus and Subtropical Fruit Journal* **614**:12.

Faton J 1970. Drip irrigation at Yuma. *Citrograph* **55**: 173-175.

Falivene S 2005. *Open hydroponics: general principles and literature review.* Land and Water Australia, National Program for Sustainable Irrigation, pp, 34-38.

Ferguson J, Davies F S, Bulger J M 1990. Fertigation and growth of young `Sunburst' tangerine trees. *Proceedings of Florida State Horticultural Science* **103**: 8-9.

Fouche P S and Bester D H 1987. The influence of water soluble fertilizer on nutrition and productivity of Navel orange trees under microjet irrigation. *Citrus and Sub-tropical Fruit Journal* **62**: 8-12.

Fritz W D 1970. Citrus Cultivation and Fertigation. *RUHR,* Stick Stoff A.G., Bochum.

Garcia Petillo M and Castel J R 2007. Water balance and crop coefficient estimation of a citrus orchard in Uruguay. *Spanish Journal of Agriculture Research* **5**(2):232-43.

Ghadekar S R, Dixit, S V and Patil V P 1989. Climatological water requirement of the citrus under Nagpur agroclimatic conditions. *PKV Research Journa,* **13** (2) : 143 - 48

Ginestar C and Castel J R 1996. Responses of young Clementine citrus trees to water stress during different phenological periods. *Journal of Horticultural Science* **74**:551-59.

Hashemi F and Gerber J F 1967. Estimating evapo transpiration from a citrus orchard with weather data. *Prceedings of American Society of Horticultural Science* **916** : 173 - 79

Haynes R J 1985. Principles of fertilizer use for trickle irrigated crops. *Fertilizers Research* **6**: 235-55.

Haynes R J 1988. Comparison of fertigation with Broad cast applications of Urea-N on levels of available soil nutrients and on growth and yield of trickle irrigated peppers. *Scientia Horticulturae,* **35**: 189-98.

Iglesias D J, Cercos M and Colmenero-Flores J M 2010. Citrus: an overview of fruiting physiology. In *Ecophysiology of Tropical Tree Crops*, Ed. F. DaMatta. New Science Publishers New York, 111-49

Intrigliolo F and Raciti G 1989. Subsurface system experiments in citrus. *Irrigation and Drainage* **36**(2): 25-27.

Jeyabaskaran K J, Shirgure P S , Pandey V, Srivastava A K and Uma S 2021. Fertigation in horticulture-a guarantee to economized quality production. *Indian Journal of Fertilizers* **17:**364-83.

Jones H G, Lakso A N and Syvertsen J P 1985. Physiological control of water status in temperate and subtropical fruit trees. *Horticultural Review* **7**:301-44.

Kelin I (983. Drip irrigation based on soil metric potentials conserves water in peach and grape. *HortScience* **18** : 942 -44.

Kriedemann P E and Barrs M D 1981. Citrus orchards. In *water Deficit and Plant Growth, vol. 6, ed.* T.T. Kozlowski. Academic Press, New York, pp.325-417.

Koo R C J (1968) Evapotrarspiration and soil moisture distribution as guide to citrus irrigation. *Proceedings of First International Citrus Symposium.* Riverside, USA, 1968, pp. 269

Koo R C J 1981).Results of Citrus fertigation studies. *Proceedings of Florida State Horticultural Science* **93:** 33-36.

Koo R C J and Smjstrala A G 1984. Effect of trickle irrigation and fertigation on fruit production and fruit quality of Valencia orange. *Proceedings of Florida State Horticultural Science* **97**:8-10 .

Legaz F, de Barreda D G, Zaragoza S and EPrimo-Millo E 1981. Interactions between water amounts and fertilizer applied through a drip irrigation system in Clementine and Satsuma mandarins. *Proeedings of International Society of Citriculture* **2**:595-98.

Leyden R F 1977. Water requirement of grapefruit in Texas. *Proceedings of International Society of Citriculture.* **3** : 1037 - 39.

Mageed K J A, Sharma B and Sinha A K 1988. Influence of irrigation and nitrogen on water use and growth of Kinnow mandarin. *Indian Journal of Agricultural Sciences* **58** (6) : 284-86.

Makhija M Sharma B and Sinha A K 1986. Estimating water requirements of Kinnow mandarin. *South Indian Horticukture* **34** (3) : 129

Marin F R and Angelocci L R 2011. Irrigation requirements and transpiration coupling to the atmosphere of a citrus orchard in southern Brazil. *Agricultural Water Management* **98**:1091-96.

Marler T E and Davies F S (1989) Microsprinkler irrigation scheduling and pattern effects on growth of young Hamlin orange trees. *Proceedings of Florida State Horticultural Science,***102**: 57-60.

Marler T E and Davies F S 1990. Micro-sprinkler irrigation and growth of young 'Hamlin orange' trees. *Journal of American Society of Horticultural Science* **115** : 45-51.

Meshram D T, Srivastava A K, Thirugnanavel A and Meshram N M 2025a. Agronomic response of subsurface versus surface drip irrigation in Nagpur mandarai (Citus reiculata Blanco) on Indian Vertisol. *Frontiers in Horticultre* **4**:1552283.

Meshram D T, Srivastava A K, Utkhede A, Pangul C and Ziogas V 2025b. Response of sensor-based fertigation of Nagpur mandarin (*Citrus reticulata* Blanco) on Vertisol of central of central India. *Horticulturae* **11**(5): 508.

Moreshet S, Cohen R and Fuchs M 1983. Response of mature '*Shomouti*' orange trees to irr igation of different soil volumes of similar levels of available water. *Irrigation Science* **3** (4) : 223 - 36

Moreshet S, Cohen Y and Fuchs M 1988. Water use and yield of a mature Shamouti orange orchard submitted to root volume restriction and intensive canopy pruning. *Proceedings of Sixth International Citrus Congress,* Tel Aviv, Israel **2**: 739-46.

Nielsen G H, Parchomchuck P, Wolk W D and Lau O L 1993. Growth and mineral composition of Newly planted apple trees following Fertigation with N and P. *Journal of American Society of Horticultural Sciences* **118**: 50-53.

Ozsan M, Tekinel O, Tuzcu O, Cevik B 1983. Studies on determining the most efficient irrigation method for growing lemons under cukurova conditions. *Doga Bilim Dergisi Dz, Tarim Ve Ormancilik,* **7**(1): 63-69.

Panigrahi P and Srivastava A K 2017.Water and nutrient management effects on water use and yield of drip irrigated citrus in Vertisol under a sub-humid region. *Journal of Integrative Agriculture* **16**(5):1184-94.

Pyle K R 1985. An appraisal of micro-irrigation for use in citrus with an emphasis on drip irrigation. *Citrus and Subtropical Fruit Journal,* **612**: 4-7.

Raciti G and Sckderi A 1977. Drip irrigation trial in citrus orchard. *Proceedings of International Society of Citriculture* **3**: 1040-45.

Raciti G and Barbagallo A 1982. Localized irrigation in lemon forcing. *Informatore Agravio,* **38(**41) : 22887-91.

Ramos A F and Santos F L 2010. Yield and olive oil characteristics of low density orchard (cv. Cordovil) subjected to different irrigation regimes. *Agricultural Water Management* **97**: 363-73.

Rana G, Katerji N and Lorenzi F de 2005. Measurement and modeling of evapotranspiration of irrigated citrus orchard under Mediterranean conditions. *Agricultural and forest Meteorology* **128**:199-209.

Randhawa G S, Singh J P and Dudani G 1960. Preliminary studies on the effect of soil management systems on soil moisture in sweet orange orchard. *Indian Journal of Horticulture* 7 : 246-249.

Ray P K and Sharma B 1990. Studies on response of young kinnow trees to irrigation. *Indian Journal of Horticulture* **47 (**3) : 291 - 96.

Reitz H J 1968. How much water do Florida citrus trees use?. *Citrus Industry* **49** (10) : 4 - 6.

Richards S J and Warnke J E 1968. Lemon irrigation management under coastal conditions. *California Citrograph* **53**:378-84.

Ribeiro R V and Machado E C 2007. Some aspects of citrus ecophysiology in subtropical climates: re-visiting photosynthesis under natural conditions. *Brazilian Journal of Plant Physiology* **19**(4):393-411.

Ribeiro R V, Rolim G de S, Azevedo F A de and Meachado E C 2008. 'Valencia' sweet orange tree flowering evaluation under field conditions. *Scientia Agricola* **65**:389-96.

Rieger M, Davies F S and Jackson L K 1986. Microsprinkler irrigation and microclimate of young orange trees during freeze conditions. *HortScience* **21**:1372-74.

Rondey D R, Roth R L and Gardner B R 1977. Citrus response to irrigation methods. *Proceedings of International Socety of Citriculture* **1**: 106-10.

Sanehez Blenco M J, Torrecillas A, Leon A and Del Amor F 1989. The effect of different irrigation treatments on yield and quality of verna lemon. *Plant and Soil* **120** (2) : 299 - 302.

Scuderi A and Raciti G 1978. Citrus trickle irrigation trials. *Proceedings of International Society of Citriculture,* pp.244-49.

Shirgure P S and Srivastava A K 2012. The effect of four under tree micro-jet irrigation (180-300^{00}) systems on fruit yield and quality of Nagpur mandarin in Central India. *Scientific Journal of Agricultural* **1** (7) :177-86.

Shirgure P S and Srivastava A K 2013a. Plant growth, leaf nutrient status, fruit yield and quality of Nagpur mandarin (*Citrus reticulate* Blanco) as influenced by potassium (K) fertigation with four potash fertilizer sources. *Scientific Journal of Crop Scienc* **2** (3) : 36-42.

Shirgure P S and Srivastava A K 2013b. Optimizing the potassium (K) dose of fertigation for the Nagpur mandarin (*Citrus reticulate* Blanco). *Agricultural Advances* **2**(8) : 242-49

Shirgure P S and Srivastava A K 2013c. Nutrient-water interaction in citrus: recent developments. *Agricultural Advances* **2**(8):224-36.

Shirgure P S and Srivastava A K 2014a. Effect of automatic micro-irrigation scheduling on productivity and quality of Nagpur mandarin (*Citrus reticulata* Blanco). *Indian Journal of Horticulture* **71** (1) : 112-16 .

Shirgure P S and Srivastava A K 2014b. Fertigation in perennial fruit crops : Major concerns. *Agrotechnology,* 3: e109. doi:10.4172/2168-9881.1000e109.

Shirgure P S and Srivastava A K 2015. Evaluation of drip irrigation emitters arrangement and its effect on soil moisture, leaf nutrients, yield and quality of Nagpur mandarin (*Citrus reticulata*). *Indian Journal of Agricultural Sciences* **85** (12): 66-71.

Shirgure P S, Srivastava A K and Huchche AD 2014. Water requirements in critical growth stages and fruit productiviy of drip irrigated Nagpur mandarin (*Citrus reticulata* Blanco). *Indian Journal of Agricultural Sciences* **84** (3) *:* 317-22.

Shirgure P S, Srivastava A K and Singh S 2000. Water management in citrus – A review. *Agricultural Reviews* **21** (4) : 223-30.

Shirgure P S, Srivastava A K and Singh S 2001a. Effect of pan evaporation based irrigation scheduling on yield and quality of drip irrigated Nagpur mandarin. *Indian Journal of Agricultural Sciences* **71** (4):264-66.

Shirgure P S , Srivastava A K and Singh S 2001b. Growth, yield and quality of Nagpur mandarin (*Citrus reticulata* Blanco) in relation to irrigation and fertigation. *Indian Journal of Agricultural Sciences* **71** (8): 547-50.

Shirgure P S, A K Srivastava and Singh S 2001c. Effect of nitrogen fertigation and band placement fertilizer application on soil -leaf nutrient build-up and incremental growth of acid lime. *Journal of Soil and Water Conservation* **45** (3&4) : 176-81.

Shirgure P S, Srivastava A K and Singh S 2001d. Effect of drip, microjets and basin irrigation method on growth, soil and leaf nutrient change in acid lime. *Indian Journal of Soil Conservation* **29** (3) : 229-34.

Shirgure P S , Srivastava A K and Singh S 2002a. Economics of drip and fertigation in acid lime orchards. *Journal of Soil and Water Conservation* **46** (1) : 56-60.

Shirgure P S, Srivastava A K and Shyam Singh S 2002b. Effect of micro-irrigation systems and basin irrigation on growth and yield of acid lime (*Citrus aurantifolia* Swingle). *Indian Journal of Citriculture* **1** (2):154-61.

Shirgure P S, Srivastava A K and Singh S 2003a. Evaluating micro-irrigation systems in Nagpur mandarin under sub-humid tropical climate. *Tropical Agriculture* **80** (2) : 91-96.

Shirgure P S , Srivastava A K and Singh S 2003b. Irrigation scheduling and fertigation in acid lime (*Citrus aurantifolia* Swingle). *Indian Journal of Agricultural Science* **73**(7) : 363-74.

Shirgure P S, Srivastava A K and Singh S 2004b. Growth, yield and quality of acid lime under pan evaporation-based drip irrigation scheduling. *Indian Journal of Soil Conservation* **32** (1) : 32-35.

Shirgure P S, Srivastava, A K and Singh S 2004c. Integrated water and nutrient management in acid lime. *Indian Journal of Soil Conservation* **32** (*2*) : 148-51.

Shirgure P S, Srivastava A K and Singh S 2004d. Citrus fertigation with a non-electric liquid dispenser. Paper presented in First Indian Horticultural Congress 2004 at IARI, New Delhi held during 6-9th November, 2004. p-206.

Shirgure P S, Srivastava A K, Singh S and Pimpale A R 2004a. Drip irrigation scheduling growth, yield and quality of acid lime (*Citrus aurantifolia* Swingle). *Indian Journal of Agricultural Sciences* **74** (2) : 92 -96.

Singh S and Srivastava A K 2004. Advances in Citriculture (ed). Jagmander Book Agency, New Delhi, India. pp.8-67.

Slack J, Turpin J W, Duncan, J H and Mckay O L 1978. Trickle irrigation of young citrus on coarse sands. *Proceedings of International Society of Citriculture* pp.124-32.

Smajstrla A G 1993. Micro-irrigation for Citrus production in Florida. *HortScience* **28**(4):295-98.

Smajstrla A G, Parsons LR, Aribi K and Yelledis G 1986. Response of young citrus trees to irrigation. *Proceedings of Florida State Horticultural Science,* **98** : 25-31.

Smith M W, Kenworthy, A L and Bedford C L 1979. The response of fruit trees to injections of Nitrogen through a trickle irrigation system. *Journal of American Society of Horticultural Sciences* **104**: 311-13.

Srivastava A K, Barlas N T, Wu Q-S, Raveh E, Brunetto G, Vashisth T, Mousavi S M and Acharya U K s2026. Climate change and citrus nutrition: mechanisms, nutrient imbalances, and inclusive management. *Frontiers in Plant Science* **17**: 1798826

Srivastava AK and Kohli R 1999. Agroecological approach for and use planning of citrus. *Agricultural Reviews* **20**(1):41-47.

Srivastava A K, Shirgure P S and Singh S 2003. Differential fertigation response of Nagpur mandarin (*Citrus reticulata* Balanco) on an alkaline Inceptisol under sub-humid tropical climate. *Tropical Agriculture* **80** (2): 97-104.

Srivastava A K and Singh S 1997. Soil suitability criteria in citrus-an appraisal. *Agricultural Reviews* **18**(3):134-46.

Srivastava A K and Singh S 2001a. Soil properties influencing yield and quality of Nagpur mandarin (*Citrus reticulata* Blanco). *Journal of Indian Society of Soil Science* **49**:226-31.

Srivastava A K and Singh S 2001b. Development of soil property norms in relation to yield and quality of *Citrus reticulata* Blanco cv. Nagpur mandarin. *Tropical Agriculture* **78**(3):174-81.

Srivastava AK and Singh S 2002a. Climate and Soil (ed), International Book Distribution Company, Lucknow, Uttar Pradesh., India Pp.216-36.

Srivastava AK and Singh S 2002b. Climate: Soil Suitability criteria . In : Citrus: Climate and Soil (ed), International Book Distribution Company, Lucknow, Uttar Pradesh, pp.291-308.

Srivastava A K and Singh S 2004. Leaf and soil nutrient guide in citrus. *Agricultural Reviews* **25**(4):225-31.

Srivastava A K and Singh S 2008. Analysis of citrus orchard efficiency in relation to soil properties. *Journal of Plant Nutrition* **30**:2077-90.

Srivastava A K, Singh S and Huchche A D 2000. Analysis on citrus flowering -a review. *Agricultural Reviews* **21**(1):1-15.

Syvertsen J P and Lloyd J 1994. Citrus. In *Handbook of Environmental Physiology of Fruit Crops,* Vol. II Sub Tropical and Tropical Crops, ed. B. Schaffer and P.C. Andersen. CRC Press Inc., Boca Raton, Florida, USA, pp.65-100.

Syvertsen J P and Smith, M L 1996. Nitrogen uptake efficiency and leaching losses from Lysimeter grown citrus trees fertilized at three nitrogen rates. *Journal of American Society of Horticultural Science* **121**(1): 57-62.

Toledo P 1982. Soil moisture level studies for upto 5-year-old 'Olinda Valencia' oranges. *Ciencia y Tecniica enla Agricultura Riego y Drenaj,* **5** (1): 17 - 30. s

Villalobos F J, Testi L and Moreno-Perez M F 2009. Evaporation and canopy conductance of citrus orchards. *Agricultural Water Management* **96**:565-73.

Wheaton T A , Parsons L R and Morgan K T 2006. Simulating annual irrigation requirement for citrus on excessively drained soils. *HortScience* **41**(6):1487-1492.

Willis L E, Davies F S and Graetz D A 1990. Fertigation effects on nitrogen leaching and growth of young ´Hamlin´orange trees on two rootstocks. *Proceedings of Florida State Horticultural Science* **103**:30-37.

Zekri M and Parsons, L R 1989. Grapefruit leaf and fruit growth in response to drip, microsprinkler and overhead sprinkler irrigation. *Journal of American Society of Horticultural Science* **114**:25-29.

Zekri M and Koo R C J 1994. Application of micronutrients to citrus trees through microirrigation system. *Journal of Plant Nutritio* **15**(11) : 2517-29.

Current Horticulture **14**(2): 36-48, April–June 2026
DOI: 10.5958/2455-7560.2026.00018.3
Received: 11 May 2026; Accepted: 15 June 2026

Advances in value-addition of horticultural crops: postharvest shelf-life extension, clean-label preservation, minimally processed products, and byproduct valorization

Raju Saravanan

ICAR – Central Tuber Crops Research Institute, Thiruvananthapuram- 695 017.Kerala, India

Abstract

India's horticulture sector is expanding rapidly, yet substantial value is lost through postharvest deterioration and quality downgrading within fresh supply chains. Recent NABCONS estimates for 2020–22 indicate postharvest losses of 6.02–15.05% in fruits, 4.87–11.61% in vegetables, and 1.29–7.33% in plantation crops and spices, with notable losses in tomato, mango, banana, onion, cassava/tapioca, chilli, turmeric, and black pepper. This review synthesises science-based pathways for value addition in Indian horticultural crops, focusing on major fruits and vegetables such as mango, banana, tomato, and onion, as well as high-value spices, while considering roots and tubers within the broader horticultural context. The review integrates the mechanistic basis of postharvest losses, including respiration, ripening, water loss, browning, pigment instability, microbial spoilage, and mechanical injury, with practical strategies for preservation and processing. It examines quality-retention approaches for minimally processed produce, including harvest maturity management, pre-cooling, cold-chain maintenance, modified atmosphere packaging, edible coatings, clean-label antimicrobials, and alternative sanitisation methods. Value addition is further highlighted through fresh-cut, ready-to-cook, ready-to-use, dehydrated, and fermented products, as well as by-product valorisation into functional ingredients and sustainable packaging materials. A matching framework is proposed to align crop perishability with feasible technologies across farm-gate, FPO/MSME, and industrial scales. Key research priorities include predictive shelf-life models, packaging–produce matching, validation of clean-label sanitation, energy-efficient cooling, and by-product valorisation supported by safety and techno-economic evidence.

Key words: Postharvest quality retention, Clean-label preservation, Minimally processed horticultural products, Smart and active packaging, Byproduct valorisation

India's horticulture sector has shifted from supplementary diversification to a leading contributor to agricultural value and nutrition. Recent national estimates put total horticultural production at about 367.72 million tonnes in 2024–25, which includes 114.51 million tonnes of fruits and 219.67 million tonnes of vegetables (PIB, 2025). At this scale, value-addition starts at harvest and extends through handling, cooling, storage, packaging, and transformation into products with longer shelf lives and higher market value.

A substantial portion of horticultural produce in India is lost or downgraded before reaching consumers or processors due to physiological deterioration, mechanical injury during harvest and transport, microbial spoilage, and inadequate temperature and humidity management. Efforts to reduce postharvest losses highlight that real improvement comes from integrated investments in technology, logistics, and operations rather than isolated interventions (PIB, 2025; Gulati *et al.,* 2024). For perishable crops such as mango, banana, tomato, onion, and certain spices—where attributes like aroma, colour, and cleanliness are critical—retaining postharvest quality is itself a means of value addition, preserving market grade, storability, and access.

Corresponding author : ritujain.iari@gmail.com

While there is extensive literature on horticultural value-addition, it remains fragmented into themes like edible coatings, smart packaging, non-thermal -sanitisation, or byproduct valorisation. What is needed is an India-specific synthesis that links commodity physiology, supply-chain capacity, and practical technology bundles. Specific reviews cover coatings and packaging (Alemu *et al.,* 2025; Moradinezhad *et al.,* 2025; Du *et al.,* 2025), and national policies emphasise integrated cold-chain and value-addition infrastructure as essential for reducing waste (PIB, 2025). For practitioners in horticulture, the priority is to relate mechanisms of deterioration to preservation pathways and to address real bottlenecks in scale-up, standardisation, quality validation, safety assurance, and supply-chain integration.

Accordingly, this review synthesises science-based pathways for value-addition in Indian horticultural crops, with emphasis on major fruits and vegetables and high-value spices, while treating roots and tubers as one component of the broader horticultural matrix. It focuses on the mechanistic basis of postharvest loss, shelf-life extension, and clean-label preservation technologies; minimally processed and convenience products; valorisation of by-products into functional ingredients and packaging materials; and smart and sustainable packaging as an emerging frontier. The central aim is to identify actionable research gaps for Indian conditions rather than to repeat commodity-wise inventories of conventional processed products. As shown in Figure 1, value addition in horticultural crops should be viewed as a continuum that begins with postharvest loss prevention and extends through shelf-life extension, processing, packaging, and by-product valorisation.

Scientific basis of postharvest deterioration: mechanistic foundation of value -addition

Postharvest deterioration results from interacting physiological, biochemical, physical, and microbiological processes. Value-addition interventions are most effective when they target these drivers directly rather than applying generic preservation measures that ignore commodity physiology and supply-chain conditions. This is particularly evident in tropical root and tuber crops such as cassava, where deterioration after harvest is closely associated with tissue injury, oxidative responses, microbial invasion, and storage temperature (Saravanan *et al.,* 2016; Saravanan *et al.,* 2020; More *et al.,* 2019).

The major deterioration drivers can be grouped into five linked processes. First, harvested produce remains metabolically active; respiration consumes sugars and organic acids, releases CO_2, water, and heat, and accelerates senescence, firmness loss, and flavour change. In climacteric fruits such as mango and banana, ethylene-mediated ripening further narrows the handling window by promoting softening, colour development, aroma formation, and greater susceptibility to decay. Second, transpiration-driven water loss causes wilting, shrivelling, turgor decline, texture weakening, and visual downgrade, particularly in vegetables and fruits stored under low relative humidity or unsuitable packaging. Third, cutting, peeling, bruising, and other injuries disrupt cellular compartmentation and promote enzymatic browning through contact between phenolic substrates and oxidative enzymes, especially polyphenol oxidase.

Pigment instability is also influenced by oxygen, pH, temperature, and antioxidant status, making browning control essential in fresh-cut and minimally processed products. Fourth, microbial spoilage is intensified by tissue injury, condensation, nutrient leakage, storage duration, and poor sanitation. Fungal decay and bacterial soft rots dominate in whole produce, while minimally processed products carry higher safety risks because natural barriers are removed and nutrient-rich surfaces are exposed. Fifth, mechanical injury during harvesting, grading, packing, and transport accelerates respiration, ethylene production, membrane damage, and pathogen entry, making supply-chain handling a direct determinant of physiological stability and market value.

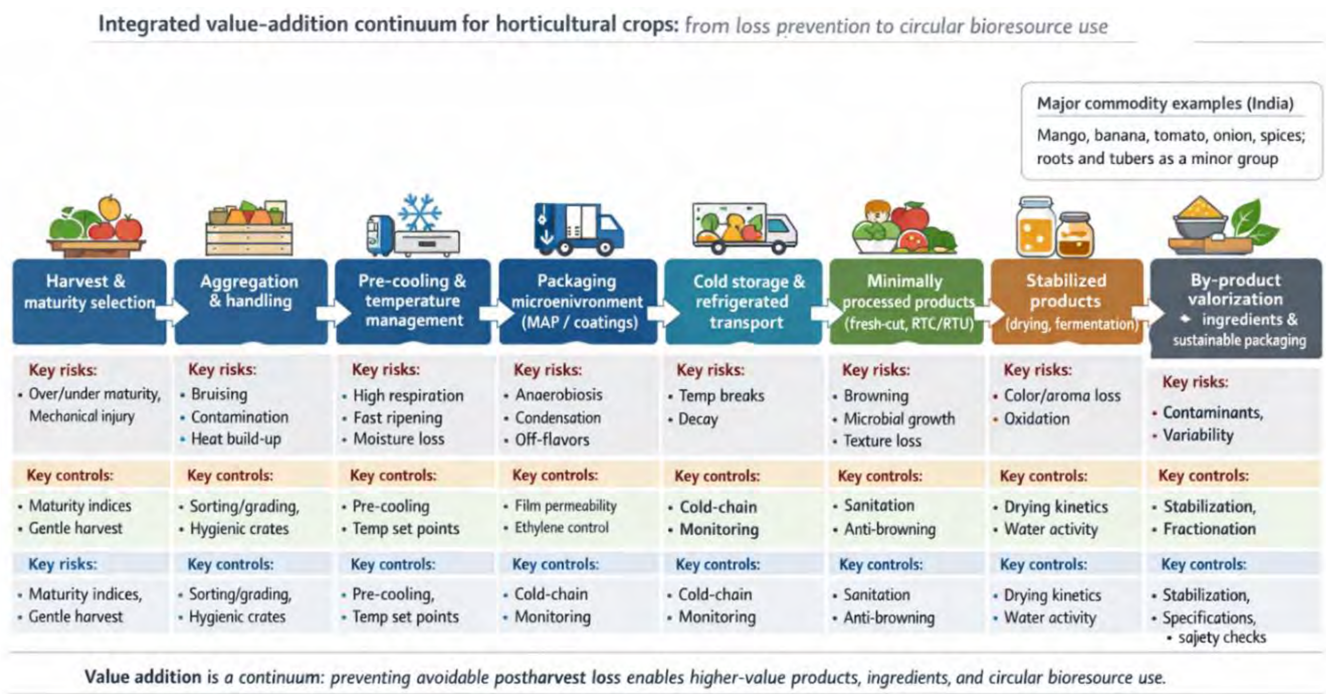


Fig. 1: Integrated value-addition continuum for Indian horticultural crops: from loss prevention to circular bioresource use

These mechanisms explain why shelf-life extension depends on integrated rather than isolated interventions. Temperature and humidity management slow respiration and water loss; modified atmospheres, edible coatings, and semi-permeable packaging regulate gas exchange and moisture movement; anti-browning dips, sanitation, and clean-label antimicrobials reduce quality loss and microbial risk; and cushioning, stack-load control, and package design limit mechanical injury. However, each intervention must be matched to commodity physiology and storage conditions. Coatings or films that are too restrictive may induce anaerobic metabolism and off-flavours, whereas poorly controlled smart or active packaging may add cost without improving operational decisions (Alemu *et al.,* 2025; Du *et al.,* 2025; Moradinezhad *et al.,* 2025). Therefore, the mechanistic foundation of value addition lies in selecting technology bundles that jointly manage respiration, ripening, moisture loss, browning, microbial spoilage, and handling stress under realistic supply-chain conditions.

Postharvest quality retention as first stage of value-addition

Value- addition in horticulture begins with preserving the biological and physical integrity of produce so that it reaches markets or processors with an acceptable grade, firmness, colour, and safety. In India, where temperature breaks, delayed movement, and handling stress are common, the most cost-effective gains often come from slowing deterioration rather than from complex downstream processing. Across commodities, the core principles are similar: remove field heat rapidly, maintain suitable temperature and relative humidity, minimise mechanical damage, and create a stable microenvironment through packaging and atmosphere management matched to the respiration and transpiration behaviour of the produce.

The postharvest behaviour of mango, banana, tomato, and onion is strongly influenced by harvest maturity and preharvest conditions, which affect firmness, flavour potential, and storage life. Harvesting too early can impair ripening uniformity and eating quality, whereas a late harvest reduces firmness and transportability. Maturity indexing is, therefore, a practical control point because even advanced coatings or packaging cannot compensate for poor initial physiological quality. Rapid pre-cooling is another critical step, as it lowers respiration, ethylene production, and moisture loss. Its performance can be improved through commodity- and package-specific optimisation of airflow, vent design, and heat transfer, showing that pre-cooling should be viewed as a heat- and mass-transfer problem linked to packaging geometry and commodity physiology rather than simply as a choice of method (Kumar *et al.,* 2023).

Cold storage remains the most effective shelf-life extension tool, but the cold chain depends on continuity from harvest to retail rather than on storage alone. Common failures include non-uniform cooling, high energy demand, and weak control, which can cause uneven ripening and localised spoilage, especially in climacteric fruits and mixed loads (Hoffmann *et al.,* 2025). Under Indian conditions, the key operational priorities are commodity-specific temperature set points, relative humidity management to reduce shrivel and weight loss, and effective monitoring, since breakdowns often result from variability within storage systems rather than from nominal set points.

Packaging and atmosphere management function as microenvironment engineering. Modified atmosphere packaging (MAP) depends on balancing produce respiration with film permeability so that O_2 consumption, CO_2 production, and gas transmission remain compatible (Caleb *et al.,* 2013). It is useful for both whole and minimally processed produce and can be strengthened by edible coatings used as complementary barrier systems (Zdulski *et al.,* 2024). However, failure can occur due to a film–commodity mismatch, condensation, or unstable temperature control, leading to anaerobiosis, off-flavours, and microbial growth. Where uninterrupted cold-chain continuity is not possible, low-energy options such as evaporative cooling can still improve quality retention at aggregation points by lowering temperature and increasing relative humidity (Basediya *et al.,* 2013).

Mechanical injury control is equally important because bruising and compression damage accelerate respiration, ethylene evolution, membrane leakage, and pathogen entry. This is especially critical in bulk handling of tomato and banana, and in mango, where surface injury and lenticel damage reduce market grade. Packaging design, therefore, affects not only transport but also cooling efficiency, humidity management, and injury risk, with ventilation geometry influencing both pre-cooling performance and produce stability (Cao *et al.,* 2020).

Quality retention must ultimately be measured in terms that reflect economic value and consumer acceptance, including firmness, colour, flavour balance, weight loss, decay incidence, and sensory shelf life. For tropical tuber crops, physiological quality retention is especially important because deterioration often begins soon after harvest and directly affects marketability, processing suitability, and shelf life (Raju, 2023; Saravanan *et al.,* 2020). The relative importance of these endpoints varies with the intended value pathway:

fresh-market mango depends heavily on appearance and firmness, whereas processing tomato may prioritise soluble solids and microbial quality. Recognising such endpoint differences helps connect postharvest science to practical value addition.

Clean-label and low-residue postharvest technologies (coatings, naturals, sanitisation, non-thermal)

Clean-label postharvest technologies aim to extend shelf life while reducing reliance on conventional chemical residues and preserving sensory, nutritional, and physiological quality. They include edible or biodegradable barrier systems, natural antimicrobials and antioxidants, and physical or non-thermal sanitation methods. Their value lies in combining microbial control with quality retention, safety, sensory acceptability, and operational feasibility.

Edible coatings are among the most widely studied interventions because they act as semi-permeable barriers to moisture and gas exchange and can also deliver active compounds. Polysaccharide-, protein-, and lipid-based coatings can reduce respiration, dehydration, and microbial growth when their permeability and application method are matched to the commodity and storage environment (Alemu *et al.,* 2025). Natural antimicrobials such as essential oils, phenolic-rich extracts, organic acids, and chitosan are increasingly incorporated into coatings and packaging systems, but their use depends on formulation stability, release behaviour, extract variability, and sensory acceptability (Aljabary *et al.,* 2025).

For fresh-cut and minimally processed products, sanitation remains a primary safety control point. Alternatives to chlorine-based systems include ozone, UV-C, cold plasma, pulsed light, ultrasound, micro- and nanobubbles, and electrolysed water (Jin and Adhikari, 2025). Their effectiveness depends on commodity sensitivity, surface characteristics, organic load, water quality, treatment uniformity, and line conditions. Electrolysed water is particularly relevant for packhouse and MSME settings because it combines antimicrobial activity with operational flexibility, although adoption requires control of pH, oxidation–reduction potential, dosing, organic load, equipment maintenance, and worker safety (Bulantekin *et al.,* 2026; Giametta *et al.,* 2025). Non-thermal interventions such as UV-C, ozonation, and cold atmospheric plasma reduce residue concerns and avoid heat damage, but their performance is constrained by surface irregularity, shadowing, limited penetration, uneven exposure, and possible surface injury if treatment intensity is not optimised (White *et al.,* 2025).

The major clean-label postharvest technologies in terms of mechanism, commodity fit, constraints, and minimum validation endpoints are given in Table 1. Overall, these technologies are complementary rather than interchangeable. Edible coatings are most useful where moisture loss, browning, and moderate respiration control are major constraints, whereas MAP is more suitable when package-atmosphere regulation is required, provided film permeability is matched to commodity respiration and storage temperature. Electrolysed water, UV-C, ozone, and cold plasma primarily serve as sanitation tools and must be integrated with hygienic handling, cooling, and appropriate packaging. Under Indian supply-chain conditions, the practical priority is to design commodity- and scale-specific technology bundles rather than promote any single preservation method: climacteric fruits require careful handling, ripening management, cooling, and compatible packaging; fresh-cut products require validated sanitation, refrigeration, and MAP or coatings; and onion and spices often benefit more from dehydration, moisture control, and high-barrier packaging.

Value-addition through minimally processed and convenience products: fresh-cut, RTC/RTU, dehydration, and fermentation

Convenience-oriented horticultural products, including fresh-cut, ready-to-cook (RTC), ready-to-use/ready-to-eat (RTU/RTE), dehydrated, and fermented products, are important value-addition routes because they convert biological perishability into consumer utility. However, they also shift the main constraints from whole-produce physiology to tissue injury, enzymatic browning, microbial safety, mass transfer, and packaging–cold chain performance. Compared with intact produce, minimally processed products generally have shorter and more safety-sensitive shelf life, requiring simultaneous control of multiple deterioration drivers.

Fresh-cut produce deteriorates rapidly because peeling, slicing, shredding, and trimming expose internal tissues, disrupt cellular compartmentation, increase respiration, stimulate wound-induced phenolic metabolism, and create nutrient-rich surfaces for microbial growth. Even under refrigeration, the shelf life of many minimally processed vegetables is often about a week, depending on commodity and handling practices (Villanova-Estors *et al.,* 2025). Fresh-cut value addition should therefore combine hygienic design, rapid cooling, atmosphere and moisture management, and targeted anti-browning and antimicrobial hurdles. Coatings and modified atmosphere packaging (MAP) are useful complementary tools because coatings

Table 1: Clean-label postharvest technologies: mechanism, best-fit commodities, and key *limitations*

Technology	Primary mechanism	Best-fit commodity / product type	Main constraints / failure modes	Validation endpoints to report (minimum set)
Edible coatings (polysaccharide/protein/lipid; sometimes with bioactives)	Semi-permeable barrier to O_2/CO_2 and water vapor; can deliver antimicrobials/antioxidants	Whole fruits (mango, banana), selected vegetables; fresh-cut (as secondary barrier)	Anaerobiosis/off-flavours if too restrictive; condensation risk; coating uniformity; sensory changes; scale-up of application/drying	Shelf-life gain (days), weight loss (%), firmness (N), colour change (ΔE), respiration/ethylene trends (if available), decay incidence (%)
Natural antimicrobials (plant extracts, essential oils, chitosan, organic acids)	Antimicrobial action via membrane disruption, pH effects, phenolic interactions; antioxidant support	Fresh-cut/RTC produce (with sensory care), decay-prone fruits, active packaging additives; spices (natural synergy)	Sensory taint (essential oils), volatility, variability in composition, regulatory/standardization, inconsistent efficacy with high organic load	Microbial log reduction, sensory acceptability, decay incidence, residue/taint assessment, stability over storage
Electrolysed water (acidic/neutral)	Oxidative inactivation (HOCl/ORP-driven), reduces surface microbial load with limited chemical residues	Fresh produce wash lines, fresh-cut/RTC pre-treatment; packhouse sanitation	Water quality dependence, dosing control, organic load reduces efficacy, worker safety, equipment costs/maintenance	Log reduction, cross-contamination control, quality retention (colour/firmness), ORP/pH/free chlorine equivalents, water reuse performance
Cold plasma / UV-C / ozone (non-thermal sanitization)	Reactive species or UV damage to microbial DNA/membranes; surface decontamination	Fresh-cut/RTC, high-risk surfaces; some fruits/vegetables where surface treatment is feasible	Shadowing/uneven exposure, limited penetration, potential surface injury or accelerated senescence, equipment cost/line integration	Log reduction, quality changes (colour/texture), shelf-life gain, treatment uniformity metrics, safety/operational parameters
Modified atmosphere packaging (MAP; passive or controlled)	Gas balance (lower O_2, higher CO_2) slows respiration and microbial growth; moisture management	Whole fruits/vegetables, fresh-cut packs, RTC mixes	Film–commodity mismatch → anaerobiosis/off-flavours; condensation and decay; temperature breaks destabilize atmosphere	Headspace O_2/CO_2 profiles, shelf-life gain, sensory acceptance, decay incidence, weight loss, browning index (fresh-cut)

reduce oxygen ingress and moisture loss, while MAP stabilises the O_2/CO_2 environment, thereby slowing browning and senescence-linked quality loss when properly designed (Zdulski *et al.,* 2024). Sanitisation options now extend beyond chlorine to non-thermal and low-residue approaches, although their practical value depends on commodity sensitivity, surface characteristics, water quality, and line conditions (Jin and Adhikari, 2025).

The RTC and RTU products, such as vegetable mixes, peeled onion, tomato preparation bases, and spice-based mixes, add value by reducing preparation time and creating outlets for processing-grade produce. Since many remain intermediate between fresh and fully shelf-stable products, their stability depends on water activity, moisture migration, microbial management, packaging atmosphere, condensation control, and cold-chain continuity (Mathew and Sharma, 2023).

Dehydration and intermediate-moisture products remain robust value-addition pathways for onion flakes and powders, tomato powders, dried vegetables, spice products, and fruit leathers or chips. Their main technical goals are to preserve colour, aroma, bioactives, texture, and rehydration quality while reducing energy use and thermal damage. Advanced and hybrid drying systems, including electromagnetic-assisted approaches, are gaining attention because they can improve drying efficiency and quality retention when optimised (Mohammed *et al.,* 2024).

Fermentation provides another stabilisation route through acidification and antimicrobial metabolite production, while also modifying flavour, functionality, and digestibility. Fermentation outcomes depend on substrate chemistry, salt or sugar regime, starter culture, and process control; therefore, functional or probiotic claims should be supported by strain-level and safety evidence rather than assumed (Gangakhedkar *et al.,* 2025; Wei *et al.,* 2025).

Across major Indian crops, fresh-cut mango and banana require rapid cooling, browning control, and carefully designed coatings or MAP; tomato is well suited to preparation bases, dehydration, sauces, and pastes; onion is particularly suited to dehydration and peel valorisation; and spices depend on drying and storage practices that preserve aroma, colour, and safety. Roots and tubers fit this framework mainly through RTC formats, dehydration, flour, starch, and related value-added ingredients. Cassava-based products illustrate how processing can convert highly perishable roots and related biomass into more stable starch-, flour-, and value-added food ingredients (Zhang *et al.,* 2025; Krishnakumar *et al.,* 2020; Hasmi *et al.,* 2025).

Byproduct valorisation and circular bioresource use: functional ingredients, pigments, fibre/pectin, and links to sustainable packaging

Byproduct valorisation is an important component of horticultural value addition because processing of mango, banana, tomato, onion, spices, and root crops generates substantial quantities of peels, pomace, seeds, kernels, trimmings, and spent biomass. These residues contain recoverable fractions such as dietary fibre, pectin and related polysaccharides, phenolics, pigments, essential-oil residues, starch, and, in some cases, proteins. The emphasis is shifting from broad waste-utilisation claims to biorefinery-style approaches in which residues are segregated, stabilised, fractionated, and standardised for defined functional, safety, storage, and regulatory targets. Figure 2 illustrates this circular valorisation pathway by linking horticultural by-product streams with recoverable fractions, functional properties, and potential food, packaging, and non-food applications.

Residue composition depends on crop type, cultivar, maturity, season, and processing chain. Mango provides peel and kernel fractions, tomato generates pigment- and fibre-rich pomace, onion produces flavonoid-rich peel and trimmings, banana contributes peel and sometimes pseudo-stem biomass, while spice processing leaves spent residues after oleoresin or essential-oil extraction. Across these streams, valorisation is strongest when materials are separated early, microbial contamination is minimised, and recovery targets are defined by measurable specifications rather than general labels such as "antioxidant extract." Fibre-rich fractions are among the most scalable because they can serve as bulking agents, texture modifiers, fat replacers, or potential prebiotic ingredients, provided particle size, sensory neutrality, and contaminant control are standardised. Protein recovery from fruit and vegetable by-products is promising, but remains limited by matrix complexity, extraction selectivity, and functionality in final formulations (Khalid *et al.,* 2025).

Natural colourants and phenolic-rich extracts are high-value targets, particularly where residues contain carotenoids, anthocyanins, flavonoids, or other bioactive compounds. Tomato pomace is relevant for carotenoids and lycopene, while onion peel is a notable source of quercetin and related flavonoids. However, pigment value depends not only on extraction yield but also on stability against light, oxygen, pH, and temperature, as well as performance in the final application. Advanced extraction and encapsulation methods are therefore important for improving pigment stability and functionality (Ramzan *et al.,* 2025; Ayub *et al.,* 2026; Sahu *et al.,* 2025).

Pectin and related polysaccharides provide a strong link between residue valorisation and sustainable packaging because they function as gelling, stabilising, film-forming, and coating materials. Their usefulness depends on extraction chemistry and structural traits such as degree of esterification, galacturonic acid content, molecular weight, and gel strength. Thus, extraction–structure–function relationships are more informative than simple yield comparisons and should guide the development of edible films, coatings, and biodegradable packaging materials (Akhter *et al.,* 2024).

Packaging is one of the clearest bridges between circular bioresource use and postharvest quality retention. Horticultural residues may serve as polymer matrices, such as pectin- or fibre-rich fractions, or as active additives, including phenolic and pigment extracts with antioxidant, antimicrobial, or UV-blocking properties. In cassava, stem biomass has also been explored as a potential industrial starch source, showing that residue valorisation can extend beyond fruit peels and pomace to structurally different crop by-products (Hasmi *et al.,* 2025). Mango peel extracts and spice-derived bioactives are increasingly discussed in active packaging systems, while biodegradable and smart films based on renewable biopolymers continue to advance through additives that improve barrier and mechanical performance (Fang *et al.,* 2025; Kumar *et al.,* 2025; Singh *et al.,* 2025; Zhang *et al.,* 2025).

A mature valorisation strategy must remain safety-led and specification-driven. Microbial loads often require stabilisation; solvent and contaminant compliance must be ensured; and phenolic-rich extracts may introduce bitterness, astringency, or colour changes. Regulatory acceptance is also critical when residue-derived fractions are intended for food, nutraceutical, or packaging applications. Therefore, by-product valorisation should be supported by toxicological evidence, quality assurance, functional validation, and techno-economic assessment rather than by circular-economy rhetoric alone (Tsegay *et al.,* 2025).

Smart, active, and sustainable packaging for horticultural value-addition (fresh chains and minimally processed products)

Packaging is now an enabling technology for horticultural value addition rather than a passive container. Modern systems regulate the produce microenvironment through O_2/CO_2 exchange, water-vapour movement, active antimicrobial or antioxidant

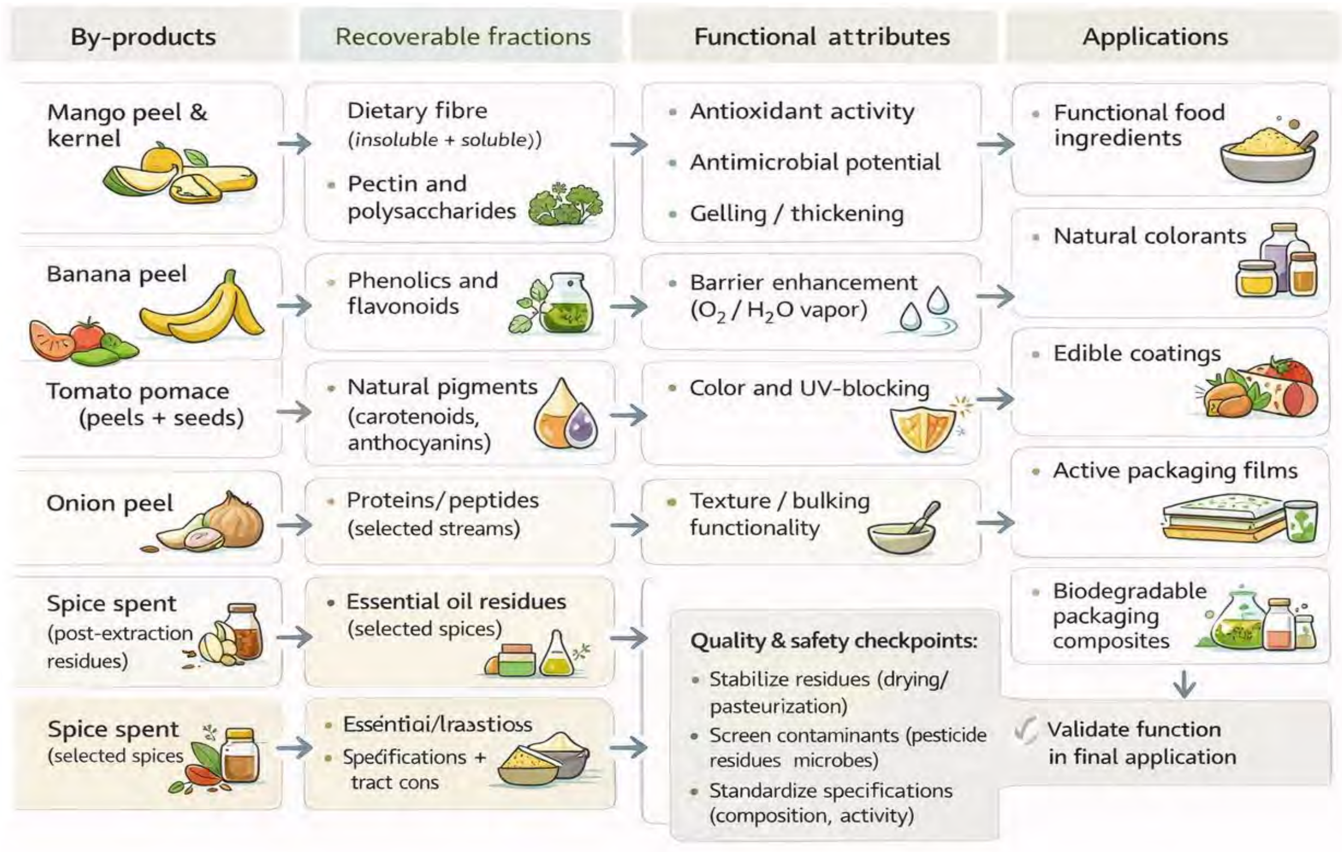


Fig. 2: Circular valorization pipeline: horticultural byproducts → fractions → fractions → applications

functions, and freshness monitoring. This is especially relevant in India, where long transport distances, uneven cold-chain continuity, repeated handling, and increasing pressure to reduce conventional plastics affect both quality retention and packaging choices.

Smart packaging includes time–temperature indicators, gas sensors for O_2, CO_2, and ethylene, freshness indicators based on pH-sensitive dyes or volatile metabolites, and biosensors linked to microbial activity. Their main value lies in risk management: they make hidden quality loss visible and can support sorting, routing, retail decisions, and shelf-life prediction. In horticultural chains, the most useful data streams are temperature history, humidity, and headspace gas trends because temperature abuse accelerates respiration, ripening, and microbial growth, while poor humidity and gas control can promote condensation, decay, anaerobiosis, and off-flavours.

Active packaging extends shelf life by interacting with the food environment through antimicrobial activity, antioxidant protection, gas scavenging or regulation, ethylene control, and moisture management. Biopolymer matrices based on polysaccharides and proteins are increasingly used as carriers for these functions because they align with sustainability goals and consumer preferences. However, their effectiveness depends on release behaviour, sensory neutrality, migration safety, and compatibility with the target commodity.

Edible films, hydrogel films, and biodegradable biopolymer materials should be treated as tunable systems rather than simple plastic substitutes. Their value depends on how material properties translate into quality outcomes: water-vapour permeability affects moisture retention and condensation risk; O_2/CO_2 permeability determines whether respiration is safely moderated or shifted toward anaerobiosis; and mechanical strength influences handling performance. Carbohydrate-based films from starch, cellulose, chitosan, pectin, alginate, or pullulan are promising, but many still have weak moisture barriers and poor stability under humid conditions, creating a need for blends, additives, and nanocomposites.

A major limitation is that packaging is often evaluated in isolation rather than matched to commodity physiology. High-respiration climacteric fruits such as mango and banana require adequate gas permeability and ethylene-responsive strategies, while fresh-cut and moisture-sensitive vegetables need condensation control, antimicrobial support, and reliable cooling. For spices and dehydrated products, packaging performance depends mainly on moisture exclusion, aroma retention, oxidation control, and mycotoxin risk reduction rather than respiration management.

For Indian supply chains, adoption will depend on unit cost, compatibility with existing crates and vented boxes, ease of interpreting indicators, performance under humid distribution conditions, regulatory acceptance of active compounds, and migration safety of additives. Smart, active, and sustainable packaging systems are most valuable when linked to specific operational decisions such as sorting, rerouting, shelf-life estimation, and waste reduction.

Commodity-wise synthesis for major Indian horticultural crops

A commodity-wise synthesis is most useful when it links dominant deterioration mechanisms with feasible value-addition routes and technology bundles. Table 2 summarises these relationships for major Indian horticultural commodities across physiological, microbial, mechanical, and processing dimensions.

Mango and banana, as climacteric fruits, require interventions that regulate ripening while preventing injury, moisture loss, and decay. The priority is an integrated bundle of maturity-based harvesting, careful handling, cooling, humidity management, ripening control, and packaging that cushions fruit while allowing adequate gas exchange. Fresh-cut mango and banana products require stricter control of browning, sanitation, and refrigeration.

Tomato value loss is driven mainly by mechanical injury, softening, water loss, and microbial spoilage, especially during ambient transport and retail handling. Gentle handling, rapid cooling, condensation control, and suitable packaging are therefore central. Fresh-cut and RTC tomato products require validated sanitation and refrigeration, whereas dehydration, sauces, pastes, and

Table 2: Major Indian horticultural commodities: dominant postharvest loss drivers and priority value-addition routes

Commodity group (examples)	Dominant loss drivers (physiological / microbial / mechanical)	Most sensitive stage (farm → aggregation → transport → retail)	Priority intervention(s) (science-led)	Priority value-added products / routes
Mango, banana (climacteric fruits)	Physiological: high respiration, ethylene-driven ripening, softening; Microbial: anthracnose/stem-end rot (latent infections); Mechanical: bruising, compression damage	Aggregation & handling; transport; retail (ripening window)	Rapid field heat removal (pre-cooling where feasible), temperature–RH management, ripening management (uniformity), cushioning + pack design to reduce bruising, packaging permeability matching (MAP/coatings), hygiene to reduce decay	Fresh-cut (limited, high control), RTC fruit pieces (strict cold chain), pulps/purees/nectars, dehydrated slices/leathers, fermentation-based beverages (where relevant), by-product capture (peel/kernel ingredients)
Tomato (soft, high-water vegetable fruit)	Physiological: rapid softening, water loss; Microbial: bacterial soft rot/fungal decay; Mechanical: bruising, cracking during handling/stacking	Transport; retail (temperature abuse); aggregation for grading	Gentle handling and stack-load management, rapid cooling priority, condensation control, MAP/coatings where suitable, sanitation for RTC/fresh-cut lines, cold-chain continuity + monitoring	RTC bases (chopped/peeled, puree), fresh-cut mixes (strict sanitation), dehydration (powder/flakes), sauces/pastes, fermentation (limited; niche), pomace valorization (pigments/fibre)
Onion (storage organ/bulb crop)	Physiological: sprouting, weight loss, dormancy break; Microbial: storage rots; Mechanical: neck/tissue damage accelerating rot	Farm/curing; storage period; transport (bulk injury)	Proper curing (neck drying, surface drying), ventilated storage basics, temperature/RH optimization for storage, sorting to remove damaged bulbs, dehydration for stabilization, improved packaging for dried products	Dehydration (flakes/powder), paste/condiments, minimally processed peeled onion (short shelf life), by-product valorization (peels □ flavonoids/extracts)
Spices (turmeric, chilli, pepper, etc.)	Physiological: quality decline mainly via oxidation and aroma loss (not senescence); Microbial/toxin: molds, mycotoxin risk when moisture is high; Mechanical: contamination and breakage during drying/handling	Drying stage; storage; retail (moisture re-entry)	Drying kinetics optimization to safe moisture/water activity, avoid re-wetting, high moisture-barrier packaging, oxygen/oxidation control, clean storage, monitoring of water activity, mycotoxin risk management protocols	Dried whole spices, powders, oleoresins/essential oils (industrial), blended spice mixes (RTC/RTU), fermentation/pickling in niche products, spice spent valorization (active packaging additives)
Others (examples: grapes/citrus/guava; leafy vegetables; floriculture produce)	Fruits: physiological (senescence, dehydration), microbial decay; Leafy veg: rapid water loss + microbes; Flowers: dehydration and senescence; Mechanical injury common	Leafy veg: transport & retail; Fruits: aggregation/transport; Flowers: transport/retail	Leafy veg: rapid cooling + high RH, hygienic handling, packaging for moisture control; Fruits: temperature set points + MAP/coatings; Flowers: hydration solutions, cooling, packaging to reduce dehydration	Fresh-cut salad/leafy mixes, minimally processed packs, juices/pulp, dehydration, fermentation products (pickles), edible coatings for shelf-life extension

intermediate-moisture products provide more robust options where cold-chain continuity is weak.

Onion requires a different approach because losses are dominated by sprouting, rotting, physiological weight loss, and storage-linked price volatility. Proper curing, sorting, ventilated storage, and humidity management are therefore more important than respiration control. Dehydration into flakes and powder remains a strong value-addition route, while onion peel offers potential for flavonoid-rich extract applications.

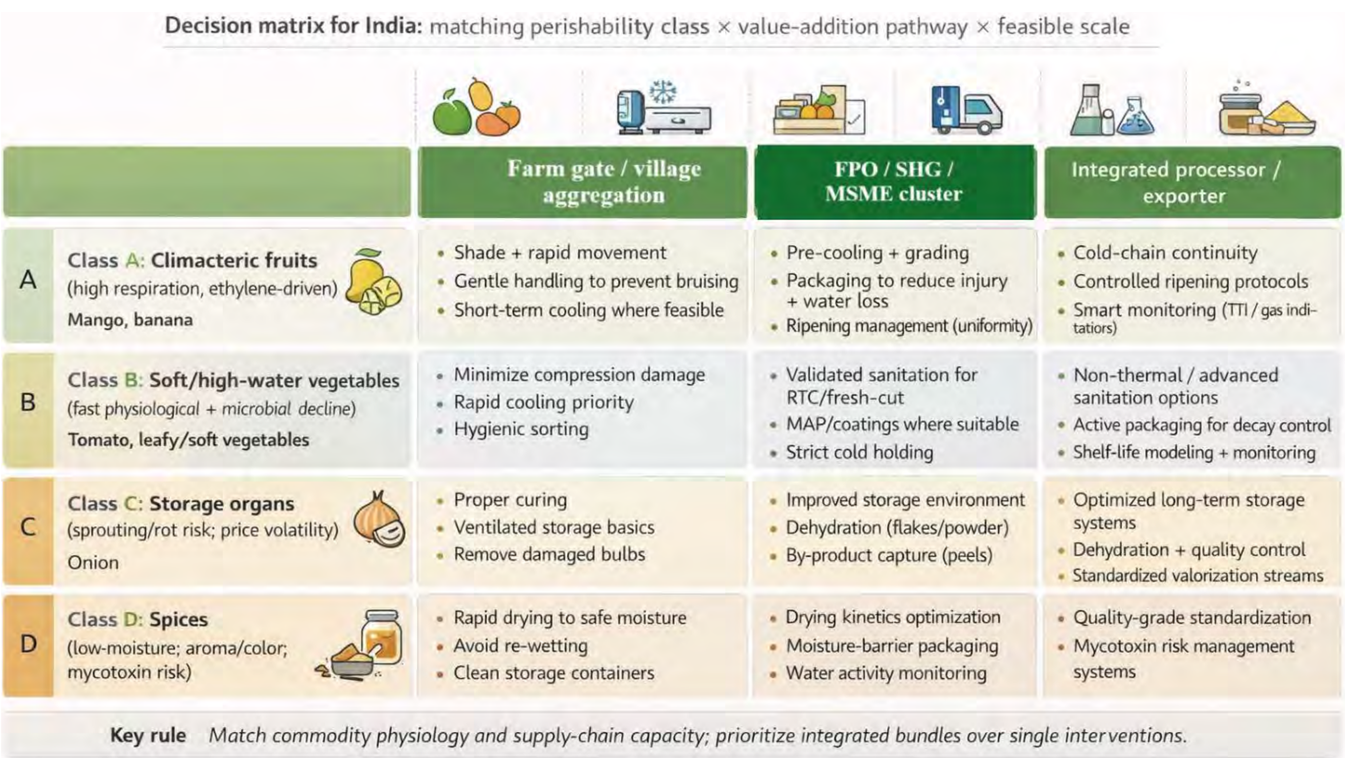
Spices are governed mainly by drying efficiency, safe moisture levels, aroma and colour retention, oxidation control, and prevention of fungal contamination or mycotoxin risk. Drying kinetics, water activity management, clean storage, and high-barrier packaging are therefore central to quality assurance. Spice-derived bioactives may also support natural preservation and active packaging when sensory effects, stability, and dosage are controlled.

Roots and tubers contribute to value addition through RTC formats, dehydration, flour production, starch- or fibre-based ingredients, and selected biodegradable material applications. In cassava, the rapid onset of postharvest physiological deterioration makes timely processing, storage-temperature management, and conversion into stable starch- or flour-based products especially important (Saravanan *et al.*, 2016; Saravanan *et al.*, 2020; Raju, 2023).

Integration framework: matching crop perishability × technology × scale.

An India-relevant value-addition framework should treat horticultural chains as combinations of commodity perishability and operational scale. The same intervention, such as modified atmosphere packaging, edible coatings, or non-thermal sanitisation, can perform very differently depending on crop physiology, time to market, temperature continuity, hygiene, and organisational capacity. Therefore, technology selection should be based on feasible bundles rather than isolated tools.

A practical matching logic can be built around two axes. The first is perishability class: high-respiration climacteric fruits such as mango and banana; high-water vegetables such as tomato and leafy or soft vegetables; storage organs such as onion, where sprouting, rotting, and price volatility interact; and low-moisture, high-value commodities such as spices, where aroma, colour, oxidation, and mycotoxin risk are critical. The second axis is scale: farm gate or village aggregation with limited equipment; FPO/SHG/MSME clusters with basic packhouse and processing capacity; and integrated processors or exporters with quality assurance, cold-chain continuity, and advanced preservation options.



Decision matrix for India: matching perishability class × value-addition pathway × feasible scale

	Farm gate / village aggregation	FPO / SHG / MSME cluster	Integrated processor / exporter
A — Class A: Climacteric fruits (high respiration, ethylene-driven) Mango, banana	• Shade + rapid movement • Gentle handling to prevent bruising • Short-term cooling where feasible	• Pre-cooling + grading • Packaging to reduce injury + water loss • Ripening management (uniformity)	• Cold-chain continuity • Controlled ripening protocols • Smart monitoring (TTI / gas indi-tatiors)
B — Class B: Soft/high-water vegetables (fast physiological + microbial decline) Tomato, leafy/soft vegetables	• Minimize compression damage • Rapid cooling priority • Hygienic sorting	• Validated sanitation for RTC/fresh-cut • MAP/coatings where suitable • Strict cold holding	• Non-thermal / advanced sanitation options • Active packaging for decay control • Shelf-life modeling + monitoring
C — Class C: Storage organs (sprouting/rot risk; price volatility) Onion	• Proper curing • Ventilated storage basics • Remove damaged bulbs	• Improved storage environment • Dehydration (flakes/powder) • By-product capture (peels)	• Optimized long-term storage systems • Dehydration + quality control • Standardized valorization streams
D — Class D: Spices (low-moisture; aroma/color; mycotoxin risk)	• Rapid drying to safe moisture • Avoid re-wetting • Clean storage containers	• Drying kinetics optimization • Moisture-barrier packaging • Water activity monitoring	• Quality-grade standardization • Mycotoxin risk management systems

Key rule *Match commodity physiology and supply-chain capacity; prioritize integrated bundles over single interventions.*

Fig. 3: Decision matrix for India: matching perishability class × value-addition pathway × feasible scale

As presented in Figure 3, the proposed decision matrix links crop perishability class with feasible value-addition pathways and operational scale under Indian conditions.

At farm-gate or village level, the priority is to slow immediate deterioration through careful handling, shading, simple grading, rapid field-heat removal, and low-energy cooling where feasible. At the FPO/SHG/MSME level, the focus shifts to predictable marketable life and basic processing stability through packhouse hygiene, short cold holding, validated sanitation, realistic MAP or coating use, dehydration, and by-product capture. At the integrated processor or exporter scale, continuous cold-chain management, controlled ripening, advanced sanitation, smart or active packaging, and systematic residue biorefinery approaches become more feasible.

Policy and investment support should reinforce continuity across pre-cooling, grading, packing, cold storage, transport, processing, and marketing because value addition in perishables depends on chain integrity rather than standalone equipment. The framework can be applied by classifying the commodity by dominant loss driver, identifying realistic infrastructure constraints, selecting a technology bundle, and evaluating performance through measurable endpoints such as shelf-life extension, weight loss, decay incidence, firmness, colour retention, safety indicators, and economic return.

Research gaps and future thrust areas (2026–2031)

Available evidence should be translated into a focused research agenda for Indian horticultural value chains, with emphasis on scalability, field-level validation, and economic feasibility. Table 3 summarises the major research gaps and future thrust areas for Indian horticultural value addition during 2026–2031.

Commodity-specific shelf-life prediction remains underdeveloped. Many studies report shelf-life extension without models that integrate temperature exposure, relative humidity, packaging atmosphere, microbial risk, and real supply-chain variability. Predictive models validated under Indian distribution conditions would support better routing, inventory decisions, technology comparison, and market planning. Packaging–produce matching also needs standardisation because poorly selected films or coatings can cause anaerobiosis, off-flavours, condensation, and decay. Future research should define practical permeability design windows for mango, banana, tomato, and common fresh-cut products under realistic storage temperatures.

Clean-label sanitation and cooling technologies require field-level validation. Laboratory performance of electrolysed water, UV-C, ozone, cold plasma, and related methods often declines under packhouse and MSME conditions due to organic load, uneven surfaces, variable water quality, shadowing, and line-speed constraints. Trials should therefore include microbial reduction, quality retention, water reuse, worker safety, cost endpoints, and comparison with existing practices. Similarly, research on low-energy pre-cooling, short-term cooling at aggregation points, and packaging designs that improve cooling efficiency should be assessed

Table 3: Research gaps and future thrusts for Indian horticultural value addition (2026–2031)

Gap theme	What is missing now	Proposed research direction	Expected outcome / impact
Predictive shelf-life models	Few commodity-specific predictive models validated under Indian temperature breaks and mixed logistics	Build models combining physiology + microbial risk + packaging, trained/validated with real chain temperature–RH data	Reliable shelf-life prediction; reduced waste; better routing/marketing decisions
Packaging–produce matching	Permeability selection is often ad hoc; frequent failures via anaerobiosis/condensation	Develop permeability "design windows" for major commodities and fresh-cut packs at realistic temperatures	Fewer packaging failures; measurable shelf-life gain; improved sensory quality
Sanitation scale-up for fresh-cut/RTC	Lab efficacy does not translate well to packhouse/MSME lines with high organic load and variable water quality	Near-industrial validation trials of electrolyzed water/non-thermal systems with SOPs for dosing, water reuse, and hygiene	Safer RTC/fresh-cut products; reproducible microbial control; higher consumer trust
Cold-chain continuity & energy efficiency	Non-uniform cooling and intermittent refrigeration remain dominant loss drivers	Engineer low-energy pre-cooling/short-term cooling and monitoring solutions for aggregation points	Loss reduction at early stages; improved grade retention; longer market window
By-product standardization	Valorization often lacks specifications, contaminant screening, and functional validation in end products	Create "specification-led" residue valorization pipelines (stabilization → screening → fraction specs → application testing)	New ingredient streams; scalable circular economy products; regulatory-ready extracts
Spices: drying–storage–mycotoxin systems	Drying, packaging, and mycotoxin risk are studied separately; integrated risk management is limited	Systems studies linking drying kinetics, water activity, packaging barrier performance, and mycotoxin monitoring	Reduced contamination risk; improved export/quality compliance; stable aroma/color retention
FPO/MSME operational models	Technology adoption fails due to weak SOPs, QA, maintenance, and market linkage design	Develop operational playbooks (SOPs, QA templates, maintenance plans) and evaluate performance in pilot clusters	Higher adoption success; improved farmer price realization; scalable decentralised value addition

through verified shelf-life extension, grade retention, and measurable loss reduction.

Byproduct valorisation must shift from broad antioxidant claims to specification-led and safety-led pathways. Future work should establish residue stabilisation protocols, contaminant screening, regulatory readiness, and extraction-to-function specifications such as pectin degree of esterification, fibre particle size, pigment stability, and bioactive performance in end-use applications. Techno-economic evaluation is essential to distinguish feasible MSME-scale value streams from laboratory demonstrations. For tropical root and tuber crops, research should also define practical shelf-life thresholds, storage-temperature responses, and processing windows that link physiological deterioration with product quality and industrial suitability (Raju, 2023; Saravanan *et al.,* 2020; Hasmi *et al.,* 2025).

Spices require integrated drying–storage–packaging research because aroma loss, colour deterioration, moisture re-entry, oxidation, and mycotoxin risk are interlinked. Systems studies should connect drying kinetics, water activity targets, packaging barrier performance, and rapid diagnostics for trader and storage environments. Decentralised value addition also needs operational research on FPO-led packhouses and micro-processing units, including SOPs, quality assurance templates, maintenance systems, skill requirements, and market linkages.

A practical five-year roadmap can therefore focus on four priorities: improving cold-chain continuity and packaging–produce matching for mango, banana, and tomato; developing MSME-ready sanitation and dehydration systems for onion and spices; standardising byproduct ingredients and bioactive packaging additives with safety assurance; and embedding digital monitoring and predictive shelf-life tools into procurement, logistics, and retail decisions.

CONCLUSION

Value- addition in Indian horticulture is best understood as a continuum that begins with preventing avoidable postharvest losses and extends to producing stable, higher-value products, ingredients, and packaging materials. Deterioration is driven by interacting processes, including respiration and ripening, water loss and texture decline, browning and pigment instability, and microbial spoilage intensified by injury and temperature abuse.

Packaging has become a central postharvest technology. Smart and active systems can support freshness monitoring, reduce oxidative and microbial deterioration, and improve risk management where cold-chain continuity is uneven. Convenience products such as fresh-cut and RTC/RTU formats offer clear value potential for mango, banana, tomato, and onion, but they require strict hygiene, rapid cooling, and well-matched MAP or coating systems. Dehydration and fermentation remain robust stabilisation pathways, especially for onion and spices, where moisture control and contamination risk strongly influence market value.

Circular valorisation of peels, pomace, and spice residues provides an important link between economic value and sustainability, but it must move beyond generic antioxidant claims toward specification-led pathways supported by stabilisation, contaminant screening, functional validation, and techno-economic assessment. Overall, value addition must be matched to commodity perishability and operational scale, from low-cost loss prevention at aggregation points to advanced ripening control, monitoring, and standardised biorefinery approaches at the industrial level. Near-term priorities include predictive shelf-life tools, packaging–produce matching rules, near-industrial validation of clean-label sanitation, and safe, standardisedvalorisation pipelines suited to Indian conditions.

REFERENCE

Akhter M J, Sarkar S, Sharmin T and Mondal S C. 2024. Extraction of pectin from powdered citrus peels using various acids: An analysis contrasting orange with lime. *Applied Food Research* **4**(2): 100614. doi: 10.1016/j.afres.2024.100614.

Alemu T T, Intipunya P and Gebeyo B A. 2025. A comprehensive review of edible coatings for postharvest management of fruits and vegetables: Enhancing food and nutrition security. *Discover Agriculture* **3**: 190. doi: 10.1007/s44279-025-00348-8.

Aljabary A M A O, Awlqadr F H, Altemimi A B, Abdulrahman A B M, Saeed M N and Hesarinejad M A. 2025. Advances in oil-based edible coatings for postharvest preservation of fruits and vegetables: A comprehensive review of biopolymer types, functional plant oils, nanoemulsion systems, and application techniques. *Journal of Agriculture and Food Research* **24**: 102425. doi: 10.1016/j.jafr.2025.102425.

Ayub H, Al Roshan A, Hossain M A, Islam M T, Kim H, Kim M J, Aziz M A, Shishir M R I, Xiao J, Lim Y Y and Suleria H A R. 2026. Anthocyanins from fruit and vegetable waste: Biosynthesis, extraction, and gut health benefits. *Food Bioscience* **62**: 107497. doi: 10.1016/j.fbio.2026.107497.

Basediya A L, Samuel D V K and Beera V. 2013. Evaporative cooling system for storage of fruits and vegetables—A review. *Journal of Food Science and Technology* **50**(3): 429–442. doi: 10.1007/s13197-011-0311-6.

Bulantekin Ö, Çiğdem A, Engin T, Russell G, et al. 2026. Electrolyzed water technologies in agri-food fields: From pesticide reduction to shelf-life extension and bioactive preservation. *Food Chemistry* **507**: 148193. doi: 10.1016/j.foodchem.2026.148193.

Caleb O J, Mahajan P V, Al-Julanda Al-Said F and Opara U L. 2013. Modified atmosphere packaging technology of fresh and fresh-cut produce and the microbial consequences—A review. *Food and Bioprocess Technology* **6**(2): 303–329. doi: 10.1007/s11947-012-0932-4.

Cao Y, Gong Y F and Zhang X R. 2020. Impact of ventilation design on the precooling effectiveness of horticultural produce—A review. *Food Quality and Safety* **4**(1): 29–40. doi: 10.1093/fqsafe/fyaa004.

Dhalsamant K, Dalai A, Pattnaik F and Acharya B. 2025. Biodegradable carbohydrate-based films for packaging agricultural products—A review. *Polymers* **17**(10): 1325. doi: 10.3390/polym17101325.

Du H, Jiang Y, Simayi A, Li C, Liu Y, Wen Y and Tang Y. 2026. Material innovation and AI-driven smart packaging for fruit and vegetable precision preservation: Applications and future trends. *Trends in Food Science & Technology* **167**: 105441. doi: 10.1016/j.tifs.2025.105441.

Du L, Huang X, Li Z, Qin Z, Zhang N, Zhai X, Shi J, Zhang J, Shen T, Zhang R and Wang Y. 2025. Application of smart packaging in fruit and vegetable preservation: A review. *Foods* **14**(3): 447. doi: 10.3390/foods14030447.

Fang Z, Zhang J, Chen Y and Wang S. 2025. Valorization of mango byproducts for sustainable active packaging: Advances in functionalized biopolymer films. *Current Research in Food Science* **11**: 100985. doi: 10.1016/j.crfs.2025.100985.

Gangakhedkar P S, Deshpande H W, Törős G, El-Ramady H, Elsakhawy T, Abdalla N, Shaikh A, Kovács B, Mane R and Prokisch J. 2025. Fermentation of fruits and vegetables: Bridging traditional wisdom and modern science for food preservation and nutritional value improvements. *Foods* **14**(13): 2155. doi: 10.3390/foods14132155.

Giametta F, Tanucci G, Ippolito A, Bianchi B and Catalano L. 2025. Sanitization treatment of fresh produce with acidic electrolyzed water: Experimental results on energy efficiency, effectiveness on rots, cost and environmental impact at near-industrial scale. *Sci.* **7**(1): 24. doi: 10.3390/sci7010024.

Gulati A, Das R and Winter-Nelson A. 2024. Reducing post-harvest losses in Indian agriculture: A case study of selected crops. Policy Brief No. 20. Indian Council for Research on International Economic Relations, New Delhi. https://icrier.org/pdf/Policy_Brief_20.pdf.

Hasmi S K K, Saravanan R, Makasana J, Thulasimani K and Safia S. 2025. Comparative study of extraction methods and screening of cassava genotypes for high stem starch yield: A potential industrial source. *Starch-Stärke* **77**(3): e202400158. doi: 10.1002/star.202400158.

Hoffmann T G, de Souza C K, Sonawane A D, Praeger U, Büchele F, Neuwald D A, Jedermann R, Linke M, Sturm B and Mahajan P V. 2025. Challenges and future perspectives in postharvest cold storage: Technological review on sustainable and efficient cold storage of fresh produce. *Food Research International* **221**: 117406. doi: 10.1016/j.foodres.2025.117406.

Jin Y and Adhikari A. 2025. Emerging and innovative technologies for the sanitization of fresh produce: Advances, mechanisms, and applications for enhancing food safety and quality. *Foods* **14**(11): 1924. doi: 10.3390/foods14111924.

Khalid L, Jabeen I, Ahmad T, Inam-ur-Raheem M, Shahid A, Cirillo T and Esposito F. 2025. Valorization of fruit and vegetable by-products for protein extraction and their functional applications in food and non-food sectors. *Food and Bioproducts Processing* **154**: 198–215. doi: 10.1016/j.fbp.2025.09.013.

Kumar A, Kumar R and Subudhi S. 2023. Numerical modeling of forced-air pre-cooling of fruits and vegetables: A review. *International Journal of Refrigeration* **145**: 217–232. doi: 10.1016/j.ijrefrig.2022.09.007.

Kumar A, Singh P, Sharma V and Kaur R. 2025. Biodegradable and smart packaging films for food quality and safety: A review. *Current Research in Food Science* **11:** 100974. doi: 10.1016/j.crfs.2025.100974.

Mathew U and Sharma P. 2023. Recent developments in ready-to-eat and ready-to-cook foods: An overview. *International Journal of Agriculture and Food Science* **5**(1): 147–152. doi: 10.33545/2664844X.2023.v5.i1b.135.

Mohammed A N, Chauhan O P and Semwal A D. 2024. Emerging technologies for fruits and vegetables dehydration. *Food and Humanity* **2**: 100303. doi: 10.1016/j.foohum.2024.100303.

Moradinezhad F, Adiba A, Ranjbar A and Dorostkar M. 2025. Edible coatings to prolong the shelf life and improve the quality of subtropical fresh/fresh-cut fruits: A review. *Horticulturae* **11**(6): 577. doi: 10.3390/horticulturae11060577.

More S J, Ravi V and Raju S. 2019. Tropical tuber crops. *In: Postharvest Physiological Disorders in Fruits and Vegetables,* pp. 719–758. De Freitas S T and Pareek S (Eds). CRC Press, Boca Raton. doi: 10.1201/b22001-33.

Press Information Bureau. 2025. Horticulture: Strengthening India's agri-economy. Second Advance Estimates 2024–25. Press Information Bureau, Government of India, 31 August 2025. https://www.pib.gov.in/PressNoteDetails.aspx?ModuleId=3&NoteId=155126&id=155126.

Press Information Bureau. 2025. NABCONS study assesses post-harvest losses across 54 crops during 2020–22. Press Information Bureau, Government of India, 1 August2025.https://www.pib.gov.in/PressReleasePage.aspx?PRID=2151371.

Raju S. 2023. Strategies for enhancing post-harvest quality and shelf life of tuber crops: Insights from physiological perspectives. *Journal of Root Crops* **47**(1&2): 40–52.

Ramzan K, Zehra S H, Balciunaitiene A, Viskelis P and Viskelis J. 2025. Valorization of fruit and vegetable waste: An approach to focusing on extraction of natural pigments. *Foods* **14**(8): 1402. doi: 10.3390/foods14081402.

Sahu C K, Vasanthkumar S, Bayineni V K, Arora A and Kadeppagari R K. 2025. Microwave and enzyme based green combinatorial process for the improved extraction of quercetin from rose onion peel. *Food Bioscience* **64:** 105991.

Saravanan R, Ravi V, Stephen R, Sheriff J T and James G. 2016. Post-harvest physiological deterioration of cassava (Manihot esculenta) – A review. *The Indian Journal of Agricultural Sciences* **86**(11): 1383–1390.

Saravanan R, Stephen R and Ravi V. 2020. Post-harvest physiological deterioration of cassava roots (Manihot esculenta Crantz) during storage under different temperatures. *Journal of Root Crops* **46**(2): 105–113.

Singh S, Habib M, Rao E S, Kumar Y, Bashir K, Jan S and Jan K. 2025. A comprehensive overview of biodegradable packaging films: Part I—Sources, additives, and preparation methods. *Discover Food* **5**: 41. doi: 10.1007/s44187-025-00303-y.

Sowbhagya H B. 2019. Value-added processing of by-products from spice industry. *Food Quality and Safety* **3**(2): 73–80. doi: 10.1093/fqsafe/fyz012.

Tadesse Tsegay Z, Smaoui S and Varzakas T. 2025. Toxicological qualities and detoxification trends of fruit by-products for valorization: A review. *Open Life Sciences* **20**(1): 20251105.

Villanova-Estors R, López-Carballo G, López-de-Dicastillo C, Correa-Guimaraes A, Gavara R and Hernández-Muñoz P. 2025. Extending the shelf life of fresh-cut vegetables with sustainable packaging: A case study on rocket leaves. *Food Packaging and Shelf Life* **50**: 101558. doi: 10.1016/j.fpsl.2025.101558.

Wei L, Van Beeck W, Hanlon M, DiCaprio E and Marco M L. 2025. Lacto-fermented fruits and vegetables: Bioactive components and effects on human health. *Annual Review of Food Science and Technology* **16**(1): 289–314. doi: 10.1146/annurev-food-052924-070656.

White S, Jackson-Davis A, Gordon K, Morris K, Dudley A, Abdallah-Ruiz A, Allgaier K, Sharpe K, Yenduri A K, Green K and Santos F. 2025. A review of non-thermal interventions in food processing technologies. *Journal of Food Protection* **88**(6): 100508. doi: 10.1016/j.jfp.2025.100508.

Zdulski J A, Rutkowski K P and Konopacka D. 2024. Strategies to extend the shelf life of fresh and minimally processed fruit and vegetables with edible coatings and modified atmosphere packaging. *Applied Sciences* **14**(23): 11074. doi: 10.3390/app142311074.

Zhang D, Ahlivia E B, Bruce B B, Zou X, Battino M, Savić D, Katona J and Shen L. 2025. The road to re-use of spice by-products: Exploring their bioactive compounds and significance in active packaging. *Foods* **14**(14): 2445. doi: 10.3390/foods14142445.

Current Horticulture **14(2): 49-57, April–June 2026**
DOI: 10.5958/2455-7560.2026.00019.X
Received: 29 March 2026; Accepted: 17 June 2026

From area expansion to sustainable intensification: yield gaps, structural constraints and vision-2047 roadmap for India's vegetable sector

Govind Pal, Hare Krishna*, Jagesh Kumar Tiwari, Neeraj Singh, Anant Bahadur, Rajesh Kumar and A.K. Singh#

ICAR- Indian Institute of Vegetable Research, Post Bag No. 1, P.O. Jakhini (Shahanshahpur), Varanasi-221305, Uttar Pradesh, India

Abstract

Vegetable cultivation plays a pivotal role in India's agricultural growth, nutritional security, and rural employment generation. During 2024–25, vegetables were grown over 11.71 million ha with a production exceeding 215.68 million tonnes, contributing nearly 58% of total horticultural output. Despite this impressive expansion, productivity has increased at slower rate, with national average yields (18.42 tonnes/ha), remaining substantially below the 25–30 tonnes/ha levels achieved in technologically-advanced systems. The widening gap between projected demand and current production trajectories underscores the urgency of yield acceleration through resource-efficient intensification. Persistent constraints, including fragmented landholdings, imbalanced nutrient application, declining soil health, climate variability, suboptimal irrigation practices, limited hybrid adoption, and significant post-harvest losses, have restricted productivity gains. Regional disparities further reflect agro-ecological limitations, infrastructural gaps, and differential technology uptake. Recent production growth has been driven more by area expansion than productivity enhancement, indicating structural inefficiencies within the system. The ICAR–Indian Institute of Vegetable Research, Varanasi, has addressed these challenges through a systems-based approach encompassing the development of climate-resilient and high-yielding varieties, precision nutrient and water management strategies, protected cultivation technologies, integrated pest management modules, and post-harvest innovations. Emphasis on balanced fertilization, resource-use efficiency, and region-specific technology packages aim to bridge productivity gaps while enhancing sustainability. Looking ahead to Vision-2047, the roadmap prioritizes seed system strengthening, soil health restoration, climate-smart production technologies, digital advisory platforms, and resilient supply chains. A shift from area-led growth to productivity-driven, low-input, and climate-resilient intensification will be critical to ensuring nutritional security, farmer profitability, and long-term sustainability of India's vegetable sector.

Key words: Climate-resilient production systems, Resource-use efficiency, Vegetable productivity, Vision-2047, Yield gap

Vegetables are central to Indian agriculture and nutritional security owing to their high productivity, short duration, economic viability, and rich micronutrient content. With improved varieties and technologies, the area under vegetables expanded to 11.71 million ha, producing 215.68 million tonnes in 2024–25 (Third Advance Estimates, Department of Agriculture & Farmers Welfare), contributing nearly 58% of total horticultural output. The sector generates substantial on- and off-farm employment and is particularly well suited to smallholders and rural women. Crop diversification toward high-value vegetables has been widely recognized as a pathway for enhancing farm profitability, employment, and sustainability in cereal-dominated systems (Choudhary *et al.*, 2025). Their labour-intensive nature strengthens rural livelihoods (Olowo *et al.*, 2022; Kandpal and Shukla, 2025), while global evidence confirms their role in poverty reduction (Thornton *et al.*, 2019). Rising incomes and dietary shifts toward micronutrient-rich foods have further accelerated vegetable demand (Avnee *et al.*, 2023; Nyamete *et al.*, 2024). Despite these strengths, productivity has increased at slower rate. The national average yield (18.42 t/ha) remains well below the 25–30 t/ha achieved in advanced systems. Even leading states such as Uttar Pradesh face crop-specific yield gaps due to fragmented holdings, nutrient imbalances, limited hybrid adoption, irrigation constraints, pest and disease pressures, and post-harvest losses.

Corresponding author : kishun@rediffmail.com
ICAR-CIAH-Central Horticultural Experiment Station, Godhra 386 340, Gujarat, India

Addressing these gaps is vital for sustaining nutritional security and farmer incomes. The Vision-2047 roadmap of ICAR–IIVR prioritizes climate-resilient varieties, region-specific technologies, balanced nutrient and water management, and resource-efficient production systems to drive sustainable productivity gains under shrinking land resources, rising input costs, and climate variability.

Growth trends and structural shifts in Indian vegetable production

Over the past three decades (1991–92 to 2024–25), India's vegetable sector has expanded substantially (Fig. 1). The cultivated area increased from 5.59 million ha to 11.71 million ha (109.48% increase), while production rose from 58.53 million tonnes to 215.68 million tonnes (268.50% increase). Productivity improved from 10.47 t/ha to 18.42 t/ha (75.93% increase). These gains were supported by improved varieties and hybrids, advancements in production and protection technologies, infrastructure development, policy support, and farmers' adoption of modern practices. India has consequently achieved near self-sufficiency in vegetables, with a surplus available for export. India's vegetable exports have shown a consistent positive growth trend over the past two decades, with a compound annual growth rate (CAGR) of 6.66% in export quantity and 14.40% in export value, reflecting the expanding role of the vegetable sector in international trade (Pal *et al.*, 2023a). However, a closer examination of growth patterns reveals structural imbalances. The compound annual growth rate (CAGR) during 1991–2021 was 4.45% for production compared to only 1.45% for productivity, indicating that output expansion has been driven more by area increase than by yield enhancement. Decadal analysis further shows that while the period 2001–2011 recorded strong gains in both areas and production, productivity growth slowed sharply after 2011, declining to below 1% per annum at the national level.

This trend suggests that earlier productivity gains achieved through varietal improvement and input intensification are now increasing at slower rate under existing management systems. The emerging productivity plateau reflects a complex interaction of agronomic, ecological, institutional, and market-related constraints, which points to the importance of a transition from area-led expansion to productivity-driven, resource-efficient intensification.

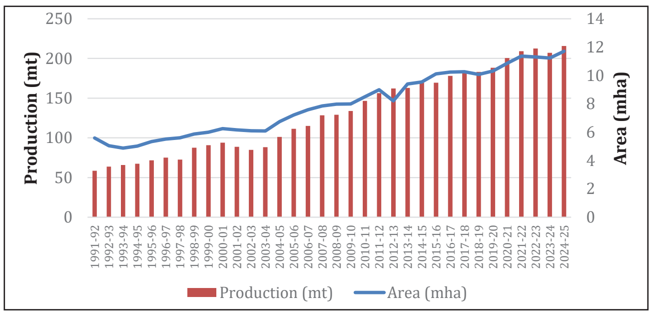


Fig. 1: Trends in area and production of vegetables in India

Decadal growth analysis (1991–2021) indicates that the highest expansion in area (4.12% p.a.) and production (6.48% p.a.) occurred during 2001–2011, while productivity growth peaked earlier (3.03% p.a.) during 1991–2001 (Table 1). Overall CAGR during 1991–2021 was 2.92% (area), 4.45% (production), and 1.45% (productivity), indicating production growth has been more area-driven than yield-led.

Recent trends (2011–12 to 2024–25) show only modest productivity gains at the national level, from 17.39 to 18.42 t/ha (5.92% increase) (Fig. 2). These improvements reflect the adoption of improved hybrids, better crop management, and supportive policy measures, though overall yield growth remains moderate.

Table 1: Compound annual growth rate of area, production and productivity of vegetables in India (1991–2021) (%)

Year	Area	Production	Productivity
1991–2001	2.14***	5.24***	3.03***
2001–2011	4.12***	6.48***	2.27***
2011–2021	2.38***	2.56***	0.67**
1991–2021	2.92***	4.45***	1.45***

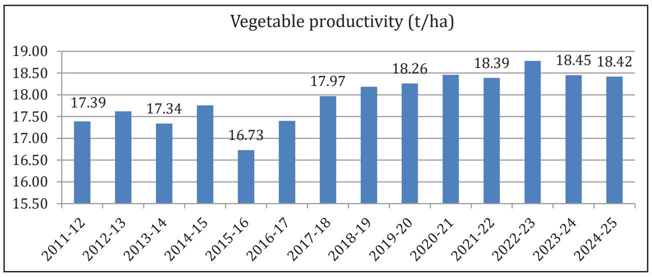


Fig. 2: National vegetable productivity trend

Vegetable availability and demand projection

India's vegetable availability has steadily improved alongside population growth (Table 2). In 2024–25, with a population of 1,450.94 million and production of 215.68 million tonnes, per capita gross and net vegetable availability reached 407.26 g/day and 285.08 g/day, respectively.

Projections indicate further increases by 2030–31, with population expected at 1,504 million and production at 258.33 million tonnes, raising gross and net availability to 470.58 g/day and 329.41 g/day. By 2040–41, production is projected to reach 316.79 million tonnes for a population of 1,593 million, translating into 544.83 g/day gross and 381.38 g/day net availability.

Rising incomes, urbanization, and dietary diversification are accelerating vegetable demand. Household demand (including food away from home) is projected to increase to 190 million tonnes by 2030–31 and 236 million tonnes by 2040–41. Total demand (household + other uses) is expected to reach 270 million tonnes in 2030–31 and 330 million tonnes in 2040–41 (Table 4). Production slightly lagged demand in 2019–20, and, under current growth trajectories, the supply gap is likely to persist unless productivity growth accelerates.

Regional productivity disparities

Vegetable productivity across Indian states shows wide disparities (Table 4), ranging from below 10 t/ha to over 30 t/ha. Andhra Pradesh records the highest average productivity (>30 t/ha). States such as Kerala, Tamil Nadu, Gujarat, Himachal Pradesh, Jammu & Kashmir, Punjab, Telangana, Tripura, and Uttar Pradesh fall within

Table 2. Population, vegetable production, and gross and net vegetable availability in India

Year	Population (million)	Vegetable production (mt)	Gross vegetable availability in gm (per capita per day)	Net vegetable availability in gm (per capita per day)
2010-11	1243.48	146.55	322.89	226.02
2015-16	1328.03	169.48	349.64	244.75
2020-21	1402.62	200.45	391.54	274.08
2021-22	1414.20	209.14	405.17	283.62
2022-23	1425.42	212.55	408.53	285.97
2023-24	1438.07	207.21	394.76	276.33
2024-25	1450.94	215.68#	407.26	285.08
Projection				
2030-31	1504.00@	258.33	470.58	329.41
2040-41	1593.00@	316.79	544.83	381.38

Note: The population estimates are converted from calendar to financial year.
3rd Advance estimates, Department of Agriculture & Farmers Welfare; @ UN projection estimates

Table 3:. Projected Vegetable Production and Demand in India

Year	Vegetable Production (mt)	Household vegetable demand (home + FAFH) (mt)	Total vegetable demand (household + other demand) (mt)
2019-20 (Actual)	188	138	199
2025-26	224	166	238
2030-31	254	190	270
2035-36	285	213	301
2040-41	318	236	330
2047-48	367	263	365

Source: Working Group report on Crop Husbandry, Agriculture Inputs, Demand and Supply (2024), NITI Aayog, New Delhi; FAFH: Food away from home

Table 4. Regional productivity patterns of vegetables across different states (TE 2023-24)

Vegetable productivity	States
>30 t/ha	Andhra Pradesh
25-30 t/ha	Kerala and Tamil Nadu
20-25 t/ha	Gujarat, Himachal Pradesh, Jammu & Kashmir, Punjab, Telangana, Tripura and Uttar Pradesh
15-20 t/ha	Bihar, Haryana, Karnataka, Madhya Pradesh and West Bengal
10-15 t/ha	Assam, Jharkhand, Maharashtra, Chhattisgarh, Meghalaya, Nagaland, Odisha and Rajasthan
<10 t/ha	Manipur, Uttarakhand, Arunachal Pradesh, Mizoram and Sikkim

the 20–30 t/ha range. Bihar, Haryana, Karnataka, Madhya Pradesh, and West Bengal have moderate productivity levels of 15–20 t/ha, while several other states fall below 15 t/ha, which is lower than the national average.

Productivity is particularly low in hilly and North-Eastern states due to a combination of agro-ecological and socio-economic constraints, including sloping terrain, soil erosion, low soil fertility, erratic rainfall, limited irrigation coverage, restricted mechanization, poor access to quality seeds and inputs, fragmented landholdings, weak infrastructure, and market isolation (Pal and Pal, 2025). These structural constraints contribute to persistent regional yield gaps, which demonstrate the importance of location-specific technological and institutional interventions.

Crop-wise yield gap analysis

Crop-wise productivity comparisons for 2023–24 (Table 5) reveal substantial inter-state variation. The overall average productivity of vegetables in Uttar Pradesh was 24.11 t/ha, which is 30.68% higher than the national average of 18.45 t/ha. Among states, Andhra Pradesh recorded the highest overall productivity (34.34 t/ha), while Mizoram registered the lowest (5.48 t/ha). Uttar Pradesh outperformed the national average in all major vegetables except green chillies.

For tomatoes, the national average was 24.97 t/ha, with Andhra Pradesh highest (45.00 t/ha) and Arunachal Pradesh lowest (6.02 t/ha). Uttar Pradesh recorded 40.01 t/ha, which is 60.23% above the national average. In brinjal, the national yield was 19.03 t/ha; Andhra Pradesh led with 50.00 t/ha, while Arunachal Pradesh recorded 3.37 t/ha. Uttar Pradesh achieved 36.04 t/ha, exceeding the national average by 89.39%.

Cabbage productivity averaged 23.58 t/ha nationally, with Tamil Nadu highest (68.74 t/ha) and Sikkim lowest (5.88 t/ha); Uttar Pradesh recorded 34.69 t/ha (+47.12%). In cauliflower, the national average was 19.31 t/ha; Tamil Nadu led (27.92 t/ha), and Kerala lagged (4.62 t/ha). Uttar Pradesh achieved 23.53 t/ha (+21.85%). For okra, the national yield was 13.12 t/ha; Andhra Pradesh recorded the highest productivity (35.00 t/ha) and Rajasthan the lowest (5.02 t/ha), while Uttar Pradesh registered 13.94 t/ha (+6.25%).

Overall, the highest productivities across crops were concentrated in Andhra Pradesh, Jammu & Kashmir, Tamil Nadu, Uttar Pradesh, and Telangana, whereas lower productivity levels were predominantly observed in NEH states, Kerala (in selected crops), and Rajasthan. These variations highlight significant yield gaps and the scope for region-specific productivity enhancement strategies.

Table 5. Vegetable productivity and gap analysis in important crops during 2023-24

Crop	National productivity (t/ha)	Productivity in Uttar Pradesh (t/ha)	% Difference in productivity (National vs. U.P.)	State with highest productivity*	State with lowest productivity *
Potato	24.57	27.55	+12.13	Andhra Pradesh (30.00)	Sikkim (7.24)
Onion	15.75	16.91	+7.37	Jammu & Kashmir (27.95)	Sikkim (6.16)
Tomato	24.97	40.01	+60.23	Andhra Pradesh (45.00)	Arunachal Pradesh (6.02)
Brinjal	19.03	36.04	+89.39	Andhra Pradesh (50.00)	Arunachal Pradesh (3.37)
Cabbage	23.58	34.69	+47.12	Tamil Nadu (68.74)	Sikkim (5.88)
Cauliflower	19.31	23.53	+21.85	Tamil Nadu (27.92)	Kerala (4.62)
Okra	13.12	13.94	+6.25	Andhra Pradesh (35.00)	Rajasthan (5.02)
Peas	10.91	13.23	+21.26	Jammu & Kashmir (21.63)	Assam (0.92)
Chillies (Green)	10.65	2.91	-72.68	Tamil Nadu (27.68)	Kerala (0.94)
Bottle gourd	16.99	31.23	+83.81	Andhra Pradesh (49.97)	Kerala (6.79)
Radish	15.87	26.83	+69.06	Tamil Nadu (35.28)	Arunachal Pradesh (1.18)
Beans	9.32	15.58	+67.17	Jammu & Kashmir (22.54)	Rajasthan (2.37)
Carrot	22.21	63.52	+186.00	Uttar Pradesh (63.52)	Sikkim (5.57)
Pumpkin	22.30	39.82	+78.57	Telangana (52.76)	Arunachal Pradesh (6.87)
Cucumber	14.70	25.89	+76.12	Jammu & Kashmir (28.81)	Arunachal Pradesh (2.86)
Bitter gourd	13.02	19.80	+52.07	Andhra Pradesh (48.01)	Mizoram (3.95)
Pointed gourd	13.14	28.05	+113.47	Andhra Pradesh (50.00)	Assam (9.58)
All vegetables	18.45	24.11	+30.68	Andhra Pradesh (34.34)	Mizoram (5.48)

**Figures in parentheses are the average productivity of the state.*

Structural, agronomic and systemic constraints in vegetable production

Despite impressive expansion in area and production, vegetable productivity in India remains constrained by interlinked structural, agronomic, climatic, and market-related factors. These constraints collectively explain the persistence of yield gaps and the recent stagnation in productivity growth.

Structural and farm-level limitations

Vegetable cultivation in India is dominated by small and fragmented landholdings, limiting economies of scale, mechanization, and adoption of precision technologies. Smallholders often face restricted access to quality seeds, protected cultivation systems, precision irrigation infrastructure, and mechanized tools. Quality seed alone contributes about 15–20% to total agricultural production, and this contribution can increase up to 40% with effective management of other inputs, highlighting the critical role of a strong seed system in enhancing vegetable productivity (Pal and Pal, 2025). Weak aggregation mechanisms and limited institutional linkages constrain technology adoption and market access. Strengthening structured market arrangements, including contract farming models, can reduce transaction costs, improve price realisation, and enhance risk-sharing between producers and buyers (NAAS, 2022c). Accelerated mechanization through smallholder-friendly equipment and custom hiring centres is essential to reduce labour dependency and enhance operational efficiency (NAAS, 2025b).

Soil health degradation and nutrient imbalance

Imbalanced fertilizer use, typically skewed toward nitrogen, has led to deficiencies of secondary and micronutrients in intensively cultivated regions. Continuous cropping without adequate organic matter replenishment has reduced soil organic carbon, impaired soil structure, and lowered nutrient-use efficiency (NAAS, 2021). As a result, nitrogen use efficiency in open-field vegetable systems often remains below 40%, increasing production costs without proportional yield gains. Long-term soil fatigue suppresses productivity even under high-input regimes.

Climate variability and abiotic stress

Vegetables, being shallow-rooted and short-duration crops, are highly sensitive to temperature fluctuations, moisture stress, and extreme weather events. Rising heat stress, erratic rainfall, waterlogging, and climate-induced pest and disease outbreaks have increased yield instability. Rainfed, peri-urban, and resource-poor regions are particularly vulnerable, necessitating climate-resilient production systems.

Regional Disparities and Technology Diffusion Gaps

Vegetable productivity varies widely across states, from below 10 t/ha in several North-Eastern and hilly regions to above 30 t/ha in technologically advanced states. These disparities reflect differences in agro-ecology, irrigation access, infrastructure, extension support, input availability, and market connectivity. In low-productivity regions, limited hybrid adoption, suboptimal crop management, and weak value-chain integration continue to widen yield gaps.

Pest, disease and input cost pressures

Vegetable crops are highly susceptible to pests and diseases, requiring frequent protection measures that account for 10–15% of total cultivation cost in intensive systems. Overreliance on chemical pesticides has increased resistance, environmental risks, and production expenses. Simultaneously, rising costs of fertilizers, irrigation, seeds, and labour have compressed profit margins, discouraging investment in advanced technologies.

Post-harvest losses and market constraints

Post-harvest losses in vegetables range between 15% and 30%, significantly reducing effective marketable surplus. Inadequate cold-chain infrastructure, poor handling, price volatility, and distress sales during seasonal gluts further erode farmer profitability. Smallholders face higher per-unit transaction costs and limited access to organized markets. Investment in decentralized packhouses, cold-chain infrastructure, and small-scale processing is critical to reducing post-harvest losses and enhancing farmer incomes. Secondary agriculture, including processing, value addition, and waste utilization, has been identified as a key pathway for increasing farm profitability and rural employment (NAAS, 2022b).

Demand–Supply Imbalance and Growth Transition

With rising population, urbanization, and dietary diversification toward micronutrient-rich foods (Yadava *et al.*, 2024; Krishna *et al.*, 2024), vegetable demand is projected to increase substantially. Diversification toward high-value crops has been recognized as a pathway for improving farm income and employment in cereal-dominated systems (Choudhary *et al.*, 2025). However, current productivity trends, averaging around 18–19 t/ha nationally, remain below the 25–30 t/ha achieved in advanced systems. Land resources are finite, and continued area expansion is neither sustainable nor sufficient to meet future demand.

ICAR-IIVR's role and interventions

The ICAR-IIVR, Varanasi, has made significant contributions in developing technologies to reduce costs and improve vegetable productivity. The institute has optimized fertigation protocols for tomato, cucumber, and okra, demonstrating yield increases of up to 70% with higher nutrient use efficiency. Integrated nutrient management models combining FYM, poultry manure, vermicompost, and biofertilizers have resulted in improved yields, enhanced soil carbon sequestration, and better pest regulation compared to chemical-only systems. The institute developed crop-specific micronutrient formulations, such as 'Kashi Sookshma Shakti/ Kashi Sookshma Shakti Plus', which boosted yields by 15–30% across crops like pea, French bean, carrot, and bottle gourd at a fraction of the cost of conventional fertilizers. IIVR has also pioneered grafting techniques in solanaceous and cucurbitaceous vegetables to combat soil-borne diseases and abiotic stresses, reducing chemical dependence and crop losses. Protected cultivation technologies, including double-stem tomato training, fertigation scheduling, and off-season hybrid production, have enhanced yield and quality while ensuring higher price realization. The institute has standardized drip irrigation and mulching packages for tomato and okra, achieving up to 56% water savings along with higher yields. Natural and organic farming modules validated by IIVR demonstrated competitive yields with reduced input costs. Additionally, innovative cropping systems like maize–pea–pumpkin and rice–vegetable–legume sequences have proven highly profitable, improving land use efficiency and farmer incomes. Varieties such as Kashi Anmol and Kashi Aman developed by ICAR–IIVR have demonstrated substantial economic benefits, including higher net returns, improved benefit–cost ratios, and significant economic surplus generation, clearly highlighting the strong impact of varietal innovations on farmer profitability and livelihood security (Pal *et al.*, 2025; Pal *et al.*, 2023b). Mechanization efforts, nutri-garden models, and bio-input formulations such as Kashi Jaiv Shakti and CRB-7 further highlight IIVR's leadership in sustainable, low-cost vegetable production.

Vegetable technology requirements in country

Given the diverse agro-climatic conditions and production constraints across states, the needs of vegetable technology must be region-specific. Broadly, priorities include improving water-use efficiency, promoting climate-resilient varieties, strengthening post-harvest systems, expanding protected cultivation, and empowering farmer collectives for improved market access.

General technology needs

- Development and dissemination of high-yielding, biofortified (NAAS, 2022a), disease-resistant and climate-resilient cultivars remain central to sustainable productivity enhancement. IIVR's contributions include non-staking bush-type legumes (Kashi Nidhi, Kashi Kanchan, Kashi Vishan, and the Kashi Bauni Sem series) that reduce labour costs, and resistant varieties such as Kashi Prakram and Kashi Sahishnu (okra, resistant to YVMV and ELCV); Kashi Arun & Kashi Krishna (carrot); and Kashi Lohit (radish) as nutritionally superior varieties; and Kashi Modak (brinjal, tolerant to shoot and fruit borer) (details in Table 7). IIVR-developed varieties have demonstrated measurable economic impact, generating ₹239.41 crore additional income and widespread adoption across 27 states (Pal *et al.*, 2023c).
- Integrated Pest and Disease Management (IPM) should be widely adopted. IIVR's validated modules, including Kashi Jaiv Shakti, CRB-7, Kashi Trichocapsule, and actinomycetes-based bioformulations, provide effective eco-friendly alternatives to chemical pesticides.
- Integrated Nutrient Management (INM), combining soil-test-based fertilizer application with organic inputs such as FYM, compost, and biofertilizers, can enhance nutrient-use efficiency. Technologies like IIVR's micronutrient formulation *Kashi Sookshma Shakti* and sensor-based fertigation protocols in tomato and capsicum demonstrate the potential to cut costs while boosting yields.
- Water-use efficiency enhancement through drip irrigation, fertigation, mulching, and sensor-based scheduling are critical for improving water productivity and reducing input costs.
- Post-harvest management through improved storage, transportation, and processing facilities is critical. IIVR has developed several value-added products (instant pumpkin halwa mix, bitter gourd encapsulation, minimally processed carrot/pumpkin) and shelf-life extension methods (wax/chitosan coating, MAP packaging). Further, integration of renewable energy solutions, including solar-powered cold storage and agro-processing units, can significantly reduce operational expenses and enhance sustainability in vegetable value chains (NAAS, 2024).
- Capacity building and collective action on farmer training, FPO strengthening, and technology dissemination are essential for scaling innovations (NAAS, 2015).
- Mechanization and cultural practices should be promoted, e.g., smallholder-friendly machinery, staking, pruning, and scientific harvesting methods can enhance fruit development, reduce losses, and improve market value. Further, grafting techniques should be promoted in stress-prone areas to enhance resistance to diseases, tolerance to abiotic stresses, and yield stability. Use of grafted Brimato/Pomato needs to be promoted for urban/terrace gardening.
- Infrastructure development, including rural roads, cold storage, decentralized packhouses, and primary processing units, will improve farmers' access to remunerative prices.

Region-specific technology needs

Coastal states

- Adoption of saline- and drought-tolerant varieties along with improved drainage systems to tackle waterlogging, salinity, and extreme weather. IIVR's work on tolerant legumes can be adapted here.

- There has been a wider use of protected cultivation structures (polyhouses, shade nets) to safeguard crops and enable off-season production (NAAS, 2010; 2019).

Hilly and NEH states

- Adoption of low-cost protected structures (naturally ventilated polyhouses, tunnels) to extend growing seasons and facilitate off-season production.
- Promotion of biofertilizers and organic farming, leveraging the region's high soil organic matter and low chemical intensification.
- We need to implement water harvesting and efficient irrigation systems to mitigate scarcity.

Arid and semi-arid states

- Emphasizes mainstreaming climate-resilient varieties and location-specific adaptation strategies.
- Innovative land-use models such as agrivoltaics, which combine crop production with solar energy generation, offer opportunities for climate buffering, income diversification, and improved resource-use efficiency (NAAS, 2025a).
- The adoption of efficient irrigation systems (drip, sprinkler) and water conservation practices (mulching, bunding, terracing, and conservation tillage) is crucial.
- Promotion of precision agriculture tools (sensor-based irrigation and fertigation) to optimize input use.
- Development and adoption of drought- and heat-tolerant varieties such as IIVR's Kashi Rituraj (radish, tolerant at 38–43°C), Kashi Tapas & Kashi Adbhut (high-set tomato varieties), Kashi Manu (climate-resilient water spinach variety) and cauliflower VRCR75-1 (curd formation at >42°C).
- Protected cultivation structures, such as greenhouses and shade nets, provide protection against extreme heat and erratic rainfall.
- Aligning crop selection and planting schedules with rainfall patterns to maximize productivity.

States with large urban populations

- Promotion of peri-urban vegetable cultivation to supply fresh produce to cities while creating local employment.
- Encouragement of urban farming initiatives (terrace, rooftop, balcony gardens). IIVR's short-duration leafy vegetable varieties and hydroponics models can be promoted for urban spaces.
- In high rainfall areas, raised-bed cultivation to ensure better drainage, warmer soil conditions, and healthier plant growth.
- In densely populated zones, technologies for container/rooftop/terrace gardening, vertical farming, hydroponics and modular protected structures are needed (NAAS, 2013). Quality seedling supply, safe inputs (water, soil), and wastewater treatment are critical (NAAS, 2022d). IIVR's short-duration leafy varieties and protocols for small-scale protected cultivation could be promoted in these settings to meet local fresh supply needs and reduce transportation/post-harvest costs.

Vision-2047 strategic framework for transforming India's vegetable sector

National cross-cutting strategic priorities

Achieving sustainable transformation of the vegetable sector requires coordinated national-level interventions that address productivity, resource efficiency, and resilience simultaneously. Central to this strategy is the development and large-scale dissemination of high-yielding, biofortified, climate-resilient, and pest- and disease-resistant varieties. Genetic improvement, including stress-tolerant cultivars and non-staking or input-efficient varieties, can reduce production risks while enhancing yield stability.

Precision resource management forms the second pillar of national strategy. Soil-test-based nutrient application, customized micronutrient formulations, nano-fertilizers, and integrated nutrient management approaches are essential for improving nutrient-use efficiency and restoring soil health. Similarly, micro-irrigation, sensor-based fertigation, mulching, and water-saving technologies are critical to enhancing water-use efficiency under conditions of declining groundwater availability.

Integrated pest and disease management (IPDM), based on resistant varieties, biological control agents, ecological engineering, and advanced diagnostics, must progressively replace excessive reliance on chemical pesticides. This transition will not only reduce production costs but also ensure safer, residue-free produce aligned with consumer demand.

Post-harvest strengthening constitutes another national priority. Investments in decentralized pack-houses, grading and sorting units, cold-chain infrastructure, and small-scale processing can significantly reduce post-harvest losses while improving farmer realization. Integration of renewable energy solutions, including solar-powered irrigation and cold storage systems (NAAS, 2024a), can further enhance sustainability and reduce operational costs.

Mechanization and digital agriculture will play a transformative role in reducing labour dependency and improving operational efficiency. Promotion of smallholder-friendly machinery, Custom Hiring Centres, drone-based applications, and AI-enabled advisory systems is essential for timely and precise farm operations (NAAS, 2024b; NAAS, 2025b).

Region-specific strategic interventions

Given India's agro-climatic diversity, regionally tailored interventions are indispensable. In coastal regions, emphasis must be placed on salinity- and waterlogging-tolerant varieties, improved drainage systems, and protected cultivation structures to buffer extreme weather events. Likewise, in hilly and North-Eastern states, low-cost protected structures such as naturally ventilated polyhouses and tunnels can extend growing seasons and enable off-season production. Promotion of biofertilizers and organic production systems can leverage the relatively low chemical intensity of these regions, while water harvesting and micro-irrigation systems can mitigate moisture variability.

Arid and semi-arid regions require climate-resilient, heat- and drought-tolerant varieties alongside efficient irrigation systems such as drip and sprinkler methods. Mulching, conservation tillage, and sensor-based fertigation are essential to optimize limited water resources. Innovative land-use models such as agrivoltaics, integrating crop production with solar energy generation, offer opportunities for climate buffering, resource-use efficiency, and income diversification (NAAS, 2025a).

States with large urban populations require expansion of peri-urban vegetable clusters and promotion of rooftop, terrace, hydroponic, and modular protected cultivation systems to address land scarcity and reduce transportation losses (NAAS, 2013). Quality seedling production systems and safe input management are critical in these intensive production zones.

Institutional and energy integration

Technological interventions must be complemented by institutional strengthening. Farmer Producer Organizations (FPOs), cooperatives, and structured market arrangements can enhance aggregation, reduce transaction costs, and improve farmer bargaining power. Contract farming models may further support market integration and risk-sharing mechanisms (NAAS, 2022c). Secondary agriculture, through processing, value addition, and waste utilization, offers substantial scope for enhancing farm incomes and generating rural employment (NAAS, 2022b). Development of decentralized processing units and cluster-based value chains can reduce post-harvest losses while stabilizing prices.

Integration of renewable energy technologies, particularly solar-powered irrigation, cold storage, and agro-processing units, will be crucial for reducing energy costs and improving environmental sustainability (NAAS, 2024a). Such convergence of agricultural and energy systems aligns with long-term climate adaptation goals.

Strategic outcomes under Vision-2047

If implemented in a phased and coordinated manner, the proposed technology framework has the potential to significantly transform India's vegetable sector by 2047. The central objective is to raise national average productivity beyond 30 t/ha through the combined adoption of climate-resilient varieties, precision nutrient management, protected cultivation, and improved agronomic practices. Enhanced micro-irrigation, sensor-based fertigation, mulching, and other water-saving technologies are expected to improve water-use efficiency by nearly 50%, strengthening sustainability under growing water scarcity. Integrated pest and disease management, through biocontrol agents, resistant cultivars, and ecological engineering, can reduce pesticide expenditure by 30–40% while ensuring safer, residue-free produce. Strengthened post-harvest systems, including decentralized packhouses, cold chain infrastructure, improved storage, and value-addition technologies, aim to reduce losses to below 10%, thereby increasing marketable surplus and farmer profitability. Renewable energy-based infrastructure, particularly solar-powered irrigation and post-harvest systems, will be critical for reducing energy costs and carbon footprint in vegetable production systems (NAAS, 2024a). Institutional innovations such as FPO-led aggregation and structured contract farming arrangements can improve market integration and farmer bargaining power (NAAS, 2015). Integrated agrivoltaic systems may further enhance sustainability by combining renewable energy generation with climate-resilient crop production (NAAS, 2025a).

Overall, Vision-2047 calls for a transition from area-led growth to productivity-driven, resource-efficient intensification supported by technological innovation and institutional reform. Scaling sustainable intensification, mechanization, and smart farming solutions will be critical to bridging yield gaps and ensuring long-term nutritional and livelihood security.

REFERENCES

Avnee, Sood S, Chaudhary DR, Jhorar P and Rana RS (2023) Biofortification: an approach to eradicate micronutrient deficiency. *Frontiers in Nutrition* 10:1233070. doi: 10.3389/fnut.2023.1233070

Chidawanyika F, Muriithi B, Niassy S, Ouya F O, Pittchar J O, Kassie M and Khan Z R (2023) Sustainable intensification of vegetable production using the cereal 'push-pull technology': benefits and one health implications. *Environmental Sustainability* 6(1): 25-34.

Choudhary R, Verma A, Kannoj Tomar, M, Kumpatla R, Nandipamu TMK (2025) Crop Diversification for Land Restoration and Food Security. In: Babu S, Das A, Rathore SS, Singh R, Singh R. (eds) Ecological Solutions to Agricultural Land Degradation. Springer, Singapore. https://doi.org/10.1007/978-981-96-3392-0_12

Kandpal AS and Shukla G (2025) Enhancing livelihood opportunities of the farming community through market linkages in the Mid-hills regions. In Lal SP, Sushmita K, Prakash S, Kethavath N and Kumari V (Eds.), Food and Nutrition Security to MitigateGlobal Hunger 'Index' apropos India (pp. 252-281). National Institute of AgriculturalExtension Management (MANAGE), Hyderabad, India.https://www.manage.gov.in/publications/eBooks/Food%20and%20Nutrition%20Security%20to%20Mitigate%20Global%20Hunger.pdf

Krishna H, Kumar R, Yadava RB, Sharma S, Verma RK, Singh MK, Tiwari SK and Bahadur A (2024) Biofortification in garden peas through multi-micronutrient formulations. *Scientia Horticulturae* 337: 113602.

NAAS (2010). Protected Agriculture in North-West Himalayas. Policy Paper No. 47, National Academy of Agricultural Sciences, New Delhi, pp. 16.

NAAS (2013) Urban and peri-urban agriculture. Policy Paper No. 67, National Academy of Agricultural Sciences, New Delhi:12 p.

NAAS (2015). Linking Farmers with Markets for Inclusive Growth in Indian Agriculture. Policy Paper No. 75, National Academy of Agricultural Sciences, New Delhi: 16 p.

NAAS (2019) Vertical farming. Policy Paper No. 89, National Academy of Agricultural Sciences, New Delhi:20 pp.

NAAS (2021) Strategies for Enhancing Soil Organic Carbon for Food Security and Climate Action. Policy Paper No. 100, National Academy of Agricultural Sciences, New Delhi: 16 pp.

NAAS (2022a) Food Fortification: Issues and Way Forward, Policy Paper No. 111, National Academy of Agricultural Sciences, New Delhi: 20 pp.

NAAS (2022b) Secondary agriculture - Challenges, opportunities and way forward. Policy Paper No. 119, National Academy of Agricultural Sciences, New Delhi:26 p.

NAAS (2022c) Contract farming for transforming Indian agriculture. Policy Paper No. 113, National Academy of Agricultural Sciences, New Delhi:20 pp.

NAAS (2022d) Utilization of wastewaters in urban and peri-urban agriculture. Policy Paper No. 106, National Academy of Agricultural Sciences, New Delhi:25 pp.

NAAS (2024a) Multiple uses of solar energy in agriculture and agro-processing. Policy Paper No. 130, National Academy of Agricultural Sciences, New Delhi:16 pp.

NAAS (2024b) Enhancing Agri-Infrastructure and Agri-Business Development through Public-Private Partnerships (PPPs) in India, Policy Paper No. 124, National Academy of Agricultural Sciences, New Delhi: 20 pp.

NAAS (2025a) Agrivoltaics for sustainable crop and energy production. Policy Paper No. 133, National Academy of Agricultural Sciences, New Delhi:17 pp.

NAAS (2025b) Accelerating farm mechanization to achieve the goal of Viksit Bharat. Policy Paper No. 135, National Academy of Agricultural Sciences, New Delhi:22 pp.

Nyamete F, Majaliwa N and Chove L (2024). Food-based intervention for boosting micronutrient status and health—A comprehensive review. *World Journal of Food Science and Technology* 8(1): 23-34.

Olowo SF, Omotayo AO, Lawal IO and Aremu AO (2022) Improving Rural Livelihood through the Cultivation of Indigenous Fruits and Vegetables: Evidence from Ondo State, Nigeria. *Agriculture* 12(3):372. https://doi.org/10.3390/agriculture 12030372

Pal G and Pal AK (2025) Seed market size in India: an economic analytical study. *International Journal of Agricultural Sciences* 21(1): 179–184.

Pal G, Roy S, Singh N, Bahadur A, Singh PM and Kumar R (2025) Economic impact assessment of chili variety Kashi Anmol. *Vegetable Science* 52(1): 65–71. doi: 10.61180/vegsci.2025.v52.i1.09

Pal G, Roy S, Singh N, Singh PM, Chaurasia SNS and Behera TK (2023a) A study on export scenario of vegetables from India: an economic analysis. *International Journal of Social Sciences* 12(3&4): 103–110.

Pal G, Roy S, Singh N, Singh PM, Yerasu SR, Yadava RB and Behera TK (2023b) Economic impact assessment of tomato var. Kashi Aman. *Vegetable Science* 50(1): 46–51. doi: 10.61180/vegsci.2023.v50.i1.06

Pal G, Singh PM, Roy S, Singh N, Bahadur A and Behera TK (2023c) A study on assessing area, production and impact of vegetable varieties from ICAR-IIVR. *Vegetable Science* 50(2): 330–337. doi: 10.61180/vegsci.2023.v50.i2.10

Thornton PK, Loboguerrero AM, Campbell BM, Kavikumar KS, Mercado L, Shackleton S (2019) Rural livelihoods, food security and rural transformation under climate change. Rotterdam and Washington, DC. Available online at www.gca.org.

Yadava RB, Kumar R, Krishna H, Yadav K, Rai N, Singh M, Singh J and Behera TK (2024) Micronutrient diversity in pole and bush type Dolichos bean germplasm: identification of gene sources from biofortification perspectives. *Plant Genetic Resources* 22(1): 50-52.

Research Article

Current Horticulture **14(2)**: 58-67, April–June 2026

DOI: 10.5958/2455-7560.2026.00020.0

Received: 31 May 2026; Accepted: 17 June 2026

Actual water consumption index of horticultural and field crops in Iran: classification into high- and low -water consuming categories

Niaz Ali Ebrahimipak and Azadeh Sedaghat*

Soil and Water Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Karaj, Iran.

Abstract

Water scarcity is a critical threat to agricultural sustainability in arid and semi-arid regions. Iran, receiving only 240 mm of annual precipitation on average, faces severe and growing pressure on its water resources, with agriculture accounting for the bulk of freshwater withdrawals. Under such conditions, accurately quantifying the actual water consumption (WRa) of crops is essential for sustainable water resource management and cropping pattern reform. This study calculated and classified the WRa for 83 field and horticulture crops across Iran, using a 10-year national dataset (2013–2023) and a mean WRa threshold of 600 mm to distinguish high water-consuming (HWC) from low water-consuming (LWC) crops. Results showed that 44 crops were classified as HWC and 28 as LWC. Among field crops, sugarcane (*Saccharum officinarum*; 3,046.8 mm), alfalfa (*Medicago sativa;* 1,603.9 mm) and Paddy rice (*Oryza sativa;* 1,249.0) exhibited the highest WRa, while carrot (255.6 mm) and celery (269.5 mm) were the lowest. Among horticulture crops, papaya (*Carica papaya*; 1,387.6 mm) and date palm (*Phoenix dactylifera*; 1,286.4 mm) exhibited the highest WRa values, followed by banana (*Musa acuminata*; 1,217.0 mm) and Sapodilla (*Manilkara zapota*; 1,132.0 mm), reflecting the exceptional evaporative demand of tropical and subtropical species cultivated in Iran's arid regions. Although the average WRa of HWC horticulture crops (838.1 mm) was lower than that of HWC field crops (1,086.2 mm), the greater number of HWC horticultural species resulted in a cumulative WRa of 36,877.9 (mm, accounting for 72.3% of the total water use within the HWC category and representing the single largest contributor to agricultural water consumption in Iran. Overall, HWC crops (44 of 83 studied) accounted for 80.3% of total agriculture water use. These findings underscore that reforming horticultural cropping patterns, particularly by restricting tropical and subtropical species with high evaporative demand and promoting low-WRa alternatives, is essential for sustainable water resource management in Iran's water-stressed agricultural sector.

Key words: Horticultural crops; Crop water requirement; Irrigation management; Iran agriculture; Water consumption index

Water scarcity represents a critical global challenge, particularly in arid and semi-arid regions, directly impacting agricultural sustainability and food security worldwide (Khorsandi *et al*., 2023). Agriculture is the predominant consumer of freshwater resources globally, making the efficient management of water in this sector essential to meet the increasing demand for food amidst diminishing water supplies (Khorsandi *et al*., 2023). The escalating pressure on natural resources, including water, necessitates the development of innovative strategies to decrease water consumption in agriculture (Preite *et al*., 2023). Global spatially explicit crop water consumption data show an overall increase of 9% for 46 agricultural crops from 2010 to 2020, with observed increases in cropland area and higher crop water consumption putting additional pressure on limited water resources (Chukalla *et al*., 2025). Iran, characterized by its arid and semi-arid climate, faces severe water limitations that threaten the sustainability of its agricultural systems (Khorsandi *et al*., 2023). The country's agricultural sector heavily relies on internal water resources, leading to substantial impacts on both renewable and non-renewable water availability, particularly groundwater (Khorsandi *et al*., 2023). Iran's focus on food self-sufficiency has historically led to an emphasis on increasing water volumes for irrigation with little attention to water use efficiency (Karandish and Hoekstra, 2017). This approach, coupled with highly subsidized water and energy, has contributed to significant groundwater table decline across the country, underscoring dysfunctional feedback relations between agricultural water and energy pricing and groundwater withdrawal in an inefficient agronomic sector (Mirzaei *et al*., 2019). Groundwater comprises up to 83% of total blue water consumption for irrigated crops in Iran, with the highest share observed in arid areas and in cereals (Karandish *et al*., 2018).

Under such conditions, accurately understanding the actual water consumption (WRa) indicator of agricultural and horticultural products is essential for improving water-use efficiency, ensuring the sustainable management of water resources (Ebrahimipak *et al*., 2026; Khorsandi *et al*., 2023). There are significant differences in the amount of virtual water required for the production of various crops. For instance, pistachios (6,327.7 L kg^{-1}) and sesame (4,157.4 L kg^{-1}) have particularly high

Corresponding author : azadehsedaghat65@gmail.com

virtual water contents, whereas as citrus fruits, tomatoes, and cucumbers are recognized as low water- consuming crops (Ebrahimipak and Sedaghat, 2025). These differences highlight the necessity of optimizing cropping patterns and improving irrigation management practices (Ebrahimipak and Sedaghat, 2025). The Water Consumption Indicator has also been introduced as one of the key indicators within the Water-Energy-Food Nexus Index (WEFNI) framework for optimizing agricultural systems (Khajavigodellou *et al.*, 2026). To mitigate these challenges, improving water-use efficiency is an urgent task, especially in arid and semi-arid areas with fragile ecosystems and severe water shortages. A fundamental step in this process involves accurately determining the actual water consumption index of various agricultural and horticultural crops. This index is primarily quantified through measurements of crop evapotranspiration (ETc) and use of crop coefficients (Kc), which relate crop water use to a reference evapotranspiration (ETo) (Allen *et al.*, 1998). Precise estimation of ETc is crucial for optimizing crop water uses, particularly in the context of agriculture and horticultural production (Bijlwan *et al.*, 2024).

Numerous studies globally have focused on determining these critical parameters for various crops under diverse climatic conditions. For instance, in semi-arid regions of Ethiopia, research using lysimeters determined the seasonal actual crop evapotranspiration (ETc) for wheat to be 427.28 mm, with corresponding crop coefficient (Kc) values of 0.43 (initial), 0.93 (mid-season), and 0.30 (end growth stage) (Bayisa *et al.*, 2024). Similarly, for sorghum in Ethiopia, the average seasonal ETc was found to be 368.07 mm, with Kc values of 0.55 (initial), 1.15 (mid), and 0.59 (end-season) (Negash *et al.*, 2023). Maize in the same region exhibited an average seasonal ETc of 507.4 mm, with Kc values of 0.55 (initial), 1.19 (mid), and 0.56 (end seasons) (Negash *et al.*, 2024). For black beans in a subtropical region, the complete growing cycle ETc was 458.31 mm, with Kc values of 0.51 for the initial stage, 0.88 for vegetative, 1.20 for flowering, and 0.85 for maturity (Gil-Marín *et al.*, 2025). Horticultural crops have also been extensively studied; for example, onion in semi-arid Ethiopia showed a pooled seasonal ETc of 460.27 mm, with Kc values of 0.68 (initial), 0.89 (developmental), 1.03 (mid), and 0.86 (late-season) (Kebede *et al.*, 2025). In California's Central Valley, agricultural water use varied significantly, with rice showing an average of 1,110 ± 85 mm yr−1 and pistachio 592 ± 352 (mm yr^{-1}) (Wong *et al.*, 2021). A comprehensive study across the United States quantified monthly crop water consumption for 30 widely irrigated crops, revealing an average annual total crop water consumption of 154.2 km^3, with corn and alfalfa identified as significant consumers (Lamsal and Marston, 2025).

Distinguishing between high- and low-water-consuming crops is crucial for developing sustainable agricultural practices in water-stressed regions. This classification is often based on crop's water use efficiency (WUE), defined as the ratio between marketable yield and seasonal actual evapotranspiration (Katerji and Mastrorilli, 2014). Factors influencing WUE variability include agro-techniques, crop species and varieties, and environmental conditions (Katerji and Mastrorilli, 2014). For instance, a study in the Heihe River Basin, China, classified crops into high-water-consuming and low-water-consuming based on their average water consumption per hectare, demonstrating that policies like tiered water pricing can significantly reduce the proportion of high-water-consuming crops planted (Li *et al.*, 2023). Research indicates that switching to lower water intensity crops can reduce consumption by up to 93%, though this may require adopting less common crop types (Boser *et al.*, 2024). Water productivity in irrigated agriculture varies widely, with horticultural products often exhibiting higher economic water productivity compared to field crops due to their higher market value (Fereres *et al.*, 2003). To cope with scarce supplies, deficit irrigation, defined as the application of water below full crop-water requirements, is an important tool to reduce irrigation water use and improve water productivity (Fereres and Soriano, 2006). Understanding these specific water consumption values and their variations is crucial for optimizing irrigation scheduling and overall water resource management.

Therefore, this study aims to investigate the WRa index horticultural and field crops in Iran. By systematically analyzing the water requirements of various crops through their evapotranspiration and crop coefficients, this research seeks to distinguish between high- and low-water-consuming species based on their direct water consumption and water use efficiency. The findings are intended to provide critical insights for optimizing crop selection, improving irrigation management practices, and informing agricultural policies that promote water conservation and enhance food security. This comprehensive assessment will contribute to the development of more resilient and water-efficient agricultural systems in the face of increasing water scarcity.

MATERIALS AND METHODS

Study area and data

Iran covering about 1,648,195 km^2, and is located between 25°03′–39°47′ N latitude and 44°14′–63°20′ E longitude, bordered by the Persian Gulf, the Gulf of Oman, and the Caspian Sea. The country is largely mountainous, with the Alborz and Zagros ranges strongly influencing its climate.Northern and western regions experience semi-humid to Mediterranean conditions, while the central plateau is mainly arid to semi-arid. Mean annual temperatures range from 22 to 26 °C and may reach up to 45 °C in summer. Annual precipitation averages around 240 mm, but varies widely from about 1,800 mm along the Caspian coast to nearly 100 mm in central deserts. About 53% of Iran is mountainous, and 47% consists of plains. This study utilized data from the NIAZAB System (Soil and Water Research Institute of Iran (http://niwr.ir)) to calculate the virtual water index for 83 field and horticultural crops across three time intervals: 10-year, 5-year, and the 2022-2023 crop year. After examining the extracted data, it was found that the data for 10-year period (2013-2023) had more stable conditions, so the 10-year period was selected.

Description of NIAZAB System

The NIAZAB system is an integrated modeling platform designed to estimate crop water requirements, irrigation demand, and scheduling at regional and county levels. It operates based on a comprehensive national database that combines hydrological, soil, and crop-related information. The system offers standardized workflows, user-friendly functionality, and the capability to locally adjust key parameters. Its database includes daily weather observations, phenological data for more than 69,000 geo-referenced crop locations, over 300 crop types, cultivated land information, irrigation efficiencies, soil properties, and recorded crop yields. The computational framework of NIAZAB is built on widely accepted hydrological and agronomic methods, including the Penman–Monteith approach for reference evapotranspiration, crop coefficient techniques, estimation of standard and actual water consumes, effective rainfall, and crop water–yield relationships. These modules are linked with spatial datasets to estimate both irrigation demand and actual water consumption at daily and 10-day time scales for each crop. By combining advanced modeling tools with extensive spatial and climatic datasets, the system provides reliable and up-to-date estimations of irrigation indicators, thereby supporting efficient and sustainable water management in the field sector.

High- and low- water consuming crops

The process of identifying high water-consuming and low water-consuming agricultural crops was carried out through a multi-stage approach. In the first stage, the water requirement, irrigation water consuming, and actual water consumption of selected field and horticultural crops were estimated using a water requirement system based on climatic data, the physical and chemical properties of soil, and phenological stages of plants. In the second stage, crops with comparative advantage and export potential were identified and prioritized using official foreign trade statistics. Subsequently, results of water requirement assessment were integrated with the list of export-oriented crops to identify those that, despite having export potential, exhibit high water consumption and are therefore in conflict with optimal cropping patterns. The indices used as the basis for classifying crops into high water-consuming and low water-consuming groups are as follows:

Net crop water requirement (ETc): The ETc refers to the amount of water required by plants under standard conditions, without any limiting environmental factors affecting plant growth (Eq. 1). These conditions include the absence of plant diseases, adequate nutrient and fertilizer supply, large-scale cultivation with optimal soil moisture, and no water stress. Under such conditions, maximum crop yield is achieved in accordance with the climatic characteristics of the region.

$$ET_c = K_c \times] \qquad \text{Eq. 1}$$

where K_c is the crop coefficient and ET_0 is the reference evapotranspiration (mm day^{-1}) (Allan *et al*., 1998). In CROPWAT 8.0, ET_0 was calculated using the FAO Penman–Monteith equation (Eq. 2). Meteorological input data, including mean wind speed, daily sunshine hours, minimum relative humidity, and average minimum and maximum air temperatures, were collected from 466 meteorological stations across the study area. Additionally, data on wheat production and cultivated area were obtained from the Agricultural Jihad Organization and the provincial statistical yearbooks.

$$ET_0 = \frac{0.408D(R_n - G) + \tilde{a}(\frac{900}{T+273})U_2(e_s - e_a)}{D + \tilde{a}(1+0.34U_2)} \qquad \text{Eq. 2}$$

where Rn is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}); T is the mean daily air temperature at 2 m elevation (°C); U_2 is the wind speed at 2 m elevation (m s^{-1}); es is the saturated water vapor pressure (kPa); ea is the actual water vapor pressure (kPa); es-ea is the water vapor pressure deficit at the reference height (kPa); Δ is the slope of the saturated water vapor pressure curve (kPa°C^{-1}); and γ is the psychrometric constant (kPa°C^{-1}).

Net irrigation water requirement (IRa): The net irrigation water requirement (IRa) is obtained as the difference between standard evapotranspiration and effective precipitation (Eq. 3)

$$IRa=ETc-Pe \quad \text{Eq. 3}$$

Pe: Effective precipitation refers to the portion of rainfall that reaches the ground surface and is stored within the plant root zone.

Actual water consumption (WRa): Actual water consumption is calculated by dividing the standard irrigation water requirement by the application efficiency (Es) (Eq. 4).

Table 1: WRa index of high water-consuming crops

Crop	Scientific name	WRa (mm)	Crops	Scientific name	WRa (mm)	Crops	Scientific name	WRa (mm)
			Horticulture crops			Field Crops		
Papaya	*Carica papaya*	1,387.6	Plum	*Prunus domestica*	750.3	Rattan sugarcane	*Saccharum officinarum*	3,046.8
Date palm	*Phoenix dactylifera*	1,286.4	Grape	*Vitis vinifera*	733.2	Alfalfa	*Medicago sativa*	1,603.9
Banana	*Musa acuminata*	1,217.0	Peach	*Prunus persica*	731.1	Paddy rice	*Oryza sativa*	1,249.0
Sapodilla	*Manilkara zapota*	1,132.0	Almond	*Prunus dulcis*	730.5	Spring Sugar Beet	*Beta vulgaris*	1,138.8
Guava	*Psidium guajava*	1,108.0	Jujube	*Ziziphus spina-christi*	726.2	Potato	*Solanum tuberosum*	1,130.6
Coconut	*Cocos nucifera*	1,063.9	Strawberry	*Fragaria × ananassa*	713.0	Onion	*Allium cepa*	1,047.9
Greengage plum	*Prunus domestica subsp. italica*	1,021.1	Fig	*Ficus carica*	705.5	Tomato	*Solanum lycopersicum*	1,036.5
Damask rose	*Rosa damascena*	967.0	Persimmon	*Diospyros kaki*	705.3	Clover	*Trifolium*	824.3
Cherry	*Prunus avium*	964.1	Mulberry	*Morus alba*	697.3	Cotton	*Gossypium hirsutum*	786.2
Apricot	*Prunus armeniaca*	941.3	Lime	*Citrus aurantiifolia*	689.5	Forage Maize	*Zea mays*	751.9
Peach	*Prunus persica*	916.7	Hazelnut	*Corylus avellana*	679.7	Grain Maize	*Zea mays*	747.2
Apple	*Malus domestica*	885.3	Pistachio	*Pistacia vera*	679.1	Tea	*Camellia sinensis*	734.1
Pear	*Pyrus communis*	874.7	Medlar	*Mespilus germanica*	670.9	Squash	*Cucurbita pepo*	720.9
Pomegranate	*Punica granatum*	871.4	Grapefruit	*Citrus × paradisi*	670.0	Bean	*Phaseolus vulgaris*	651.5
Walnut	*Juglans regia*	863.9	Orange	*Citrus sinensis*	670.0	Sesame	*Sesamum indicum*	639.8
Quince	*Cydonia oblonga*	844.2	Jujube	*Ziziphus jujuba*	659.8	Eggplant	*Solanum melongena*	621.5
Nectarine	*Prunus persica var. nucipersica*	828.4	Sweet Lime	*Citrus limetta*	641.3	Sunflower	*Helianthus annuus*	612.0
Sour cherry	*Prunus cerasus*	821.4	Raspberry	*Rubus idaeus*	609.4	-	-	-
Peach	*Prunus persica*	819.9	-	-	-	-	-	-
Mandarin	*Citrus reticulata*	806.0	-	-	-	-	-	-
Mango	*Mangifera indica*	799.7	-	-	-	-	-	-
Olive	*Olea europaea*	774.0	-	-	-	-	-	-
Maximum		1387.6				Maximum		3046.8
Minimum		609.4				Minimum		612.0
Average		841.4				Average		1020.2
Total Horticultural		33656.1				Total Field		17342.9
Total (Horticultural and Field Crops)				50999				

Table 2. WRa index of low water-consuming crops

Crops	Scientific name	WRa(mm)	Crop	Scientific name	WRa(mm)	Crops	Scientific name	WRa(mm)
Horticulture crops			Field Crops					
Barberry	*Berberis vulgaris*	556.5	Tobacco	*Tobacco*	556.5	Turnip	*Brassica rapa subsp. rapa*	419.0
Cornelian cherry	*Cornus mas*	496.0	Greenhouse cucumber	*Greenhouse cucumber*	553.2	Cucumber	*Cucumis sativus*	409.2
-	-	-	Chickpea	*Chickpea*	548.0	Cabbage	*Brassica oleracea var. capitata*	396.0
-	-	-	Pecan	*Pecan*	539.8	Barley	*Hordeum vulgare*	392.0
-	-	-	Hawthorn	*Hawthorn*	513.7	Saffron	*Crocus sativus*	379.0
-	-	-	Soybean	*Soybean*	506.2	Lettuce	*Lactuca sativa*	364.8
-	-	-	Melon	*Melon*	503.4	Canola	*Brassica napus*	338.0
-	-	-	Wheat	*Wheat*	483.0	Autumn sugar beet	*Beta vulgaris*	296.5
-	-	-	Watermelon	*Watermelon*	456.0	Kiwifruit	*Actinidia deliciosa*	269.6
-	-	-	Lentil	*Lentil*	452.0	Celery	*Apium graveolens*	269.5
-	-	-	Oleaster	*Oleaster*	445.0	Pepper	*Capsicum annuum*	263.0
-	-	-	Cantaloupe	*Cantaloupe*	436.9	Carrot	*Daucus carota subsp. sativus*	255.6
-	-	-	Sumac	*Sumac*	427.0	-	-	-
-	-	-	Cumin	*Cuminum cyminum*	420.0	-	-	-
Maximum		556.54		Maximum	556.50			
Minimum		495.98		Minimum	255.56			
Average		526.26		Average	423.57			
Total Horticulture		1,052.5		Total Field	11,436.3			
Total (Horticultural and field crops)					12488.85			

WRa=IRa/Es Eq. 4

In this study, the mean WRa index was employed as a threshold criterion to quantitatively and data-drivenly classify a wide range of field and horticultural crops into water-intensive and low water- consuming categories. Compared with the qualitative or arbitrary classifications adopted in many previous studies, this approach provides greater statistical robustness, as the 600 mm threshold was derived from the actual distribution of the dataset rather than from theoretical assumptions. Overall, 44 crops were classified as water-intensive, whereas 28 crops fell into the low water- consuming category. This asymmetric distribution indicates that a considerable proportion of Iran's agricultural crop portfolio imposes substantial pressure on water resources.

RESULTS AND DISCUSSION

Actual water consumption index (WRa)

The WRa, refers to the amount of water delivered to the field based on irrigation application efficiency and the actual irrigation water requirement of different crops (Ahmed *et al*., 2024). Based on this index, the WRa of agricultural and horticultural crops was extracted in Tables 1 and 2.

The Wray index also incorporates the effects of irrigation method, irrigation efficiency, and water losses (Ahmed *et al*., 2024), the mean value of this index was considered as the threshold distinguishing low water-consuming crops from high water-consuming crops (Ebrahimipak and Sedaghat, 2025). In this study, the average value of the WRa index was 600 mm. Therefore, crops with WRa greater than 600 mm are classified as high water-consuming crops, whereas crops with actual water consumption less than 600 mm are classified as low water-consuming crops.

Within the water-intensive category (Table 1), the horticultural subgroup dominated the upper end of the WRa spectrum, with tropical and subtropical species recording the highest values. Papaya (*Carica papaya*; 1,387.6 mm), date palm (*Phoenix dactylifera*; 1,286.4 mm), banana (*Musa acuminata*; 1,217.0 mm), sapodilla (*Manilkara zapota*; 1,132.0 mm), guava (*Psidium guajava*; 1,108.0 mm), coconut (*Cocos nucifera*; 1,063.9 mm), and greengage plum (*Prunus domestica subsp. italica*; 1,021.1 mm) were the most water-intensive horticultural crops, reflecting the high evaporative demand and year-round growing cycles characteristic of these species in Iran's southern and coastal provinces. Although sugarcane (*Saccharum officinarum*; 3,046.8 mm) recorded the single highest WRa among all crops, the cumulative WRa of water-intensive horticultural crops (33656.1 mm) far exceeded that of water-intensive field crops (17342.9 mm), confirming that the horticultural sector as a whole represents the dominant driver of agricultural water consumption in Iran.

Among water-intensive horticulture crops (Table 1), papaya (*Carica papaya*; 1,387.6 mm) and date palm (*Phoenix dactylifera*; 1,286.4 mm) ranked highest in terms of WRa. Both crops are tropical or subtropical species cultivated in regions characterized by extremely high atmospheric evaporative demand. In the same horticultural spectrum, crops such as banana (*Musa acuminata*; 1,217 mm) and Sapodilla (*Manilkara zapota;* 1,132.0 mm) also exhibited remarkably high WRa values. This finding is particularly concerning for rice cultivation, which has expanded in provinces such as Gilan and Mazandaran, where water resources have experienced increasing stress in recent years.

A comparison of the mean values of the two water-intensive subgroups reveals an important pattern. The average WRa of water-intensive field crops (1,086.2 mm) was substantially higher than that of water-intensive horticultural crops (841.4 mm), indicating that, on average, each water-intensive field crop consumes approximately 29.6% more water than its horticultural counterpart. Nevertheless, because the number of water-intensive horticultural crops considerably exceeds that of field crops, the cumulative WRa of the horticulture subgroup (33656.1 mm) accounts for nearly 72.3% of the total WRa within this category. This highlights the dominant contribution of the horticulture sector to agricultural water consumption in Iran. Crops with WRa values ranging between 600 and 750 mm, including raspberry (*Rubus idaeus;* 609.4 mm), Sweet lime (*Citrus limetta*; 641.3 mm), and jujube (*Ziziphus jujuba*; 659.8 mm), constitute a highly important transitional group. Although these crops were classified as water-intensive based on the selected threshold, from a management perspective they possess the greatest potential for shifting into the low water- consuming category through the adoption of advanced irrigation technologies, such as drip irrigation, regulated deficit irrigation, and precision irrigation management. Consequently, prioritizing this transitional group in extension and research programmes could yield the most immediate and effective reductions in agricultural water consumption in the short term.

The low water-consuming group exhibits a markedly different and statistically more compact structure compared with water-intensive group (Table 2). The WRa range within this category extends from 255.6 (mm) for carrot (*Daucus carota subsp. sativus*) to 556.5 (mm) for tobacco (*Tobacco*) and barberry (*Berberis vulgaris*), representing a spread of approximately 301 mm. In contrast to the more than 2,437 mm range observed in the water-intensive group, this narrower distribution indicates a substantially greater degree of homogeneity and clustering among low water-consuming crops.

The most significant finding in this group is presence of strategic cereal and oilseed crops. Wheat (*Wheat*), with a WRa of 483 (mm), barley (*Hordeum vulgare*) with 392 (mm), and canola (*Brassica napus*) with 338 (mm), are all key components of the country's food security system and were classified within low water- consuming category. This finding is particularly important because it suggests that food security and water security are not necessarily conflicting objectives; rather, they can be aligned through the promotion of crops that simultaneously exhibit strategic agricultural value and relatively low water requirements. Therefore, expanding the cultivation of these crops in arid and semi-arid regions appears justifiable from a water resource management perspective.

Within the low water- consuming horticultural subgroup (Table 2), the presence of barberry (*Berberis vulgaris*; 556.5 mm) and kiwifruit (*Actinidia deliciosa*; 269.6 mm) at the two extremes of the spectrum is particularly noteworthy. Barberry, a native crop of the Khorasan region cultivated under semi-arid conditions, exhibited a relatively moderate WRa within the low water- consuming category. In contrast, kiwifruit (*Actinidia deliciosa*), which is often perceived as a water-intensive crop, recorded a WRa of only 269.6 mm, placing it among the lowest values within this group. These finding challenges conventional assumptions regarding the water requirements of kiwifruit (*Actinidia deliciosa*) cultivation and may open new avenues for research on optimizing horticultural roduction under water-limited conditions. Furthermore, the overwhelming dominance of field crops within this category, accounting for 91.6% of the total WRa of low water- consuming crops, clearly indicates that Iran's field crop sector is substantially better aligned with water-scarcity conditions than the horticulture sector. This distinction highlights the comparatively greater adaptability of field crop production systems to arid and semi-arid environments.

The findings of this study showed substantial agreement with previous research. Based on the available literature, actual water consumption in horticultural crops varies considerably depending on crop type and environmental conditions. For instance, Ichwan et al. (2022) reported that pepper plants consumed approximately 151 (mL) of water per day under field capacity (FC) conditions, while irrigation at 50% of field capacity was found to be unsuitable due to its adverse effects on plant performance. Similarly, Zamani et al. (2024), in a study of horticultural crops in Iran, identified walnut as having the highest water scarcity footprint, reaching 2,652.78 (m^3 t^{-1} (, indicating substantial water requirements and significant environmental impacts associated with its production. Keyser-Gibson et al. (2025) investigated ornamental species, including Cercis occidentalis and Physocarpus opulifolius, and demonstrated that irrigation volumes could be significantly reduced without negatively affecting plant growth or overall performance. These findings highlight the potential for improving water-use efficiency through optimized irrigation management. Collectively, the available evidence emphasizes the critical importance of adopting crop-specific water management strategies to improve water productivity and support long-term agricultural sustainability.

Among horticultural crops, pistachio also exhibited a relatively high WRa value (679.1 mm).

This finding is consistent with the results reported by Ebrahimipak and Sedaghat (2025), who identified pistachio as one of the horticulture crops with the highest virtual water consumption, estimated at 6,327.7 (L kg^{-1}). Therefore, the expansion of pistachio (*Pistacia vera*) cultivation in regions facing water scarcity should be accompanied by more precise and sustainable water resource management practices. The mean WRa of water-intensive crops is approximately 2.1 times greater than that of low water- consuming crops (Fig 1). Moreover, the total cumulative WRa of water-intensive group reached 50,999 mm, compared with 12,488.85 mm for the low water- consuming group, representing a ratio of more than 4:1. This both horticultural and field crops, account for nearly 80.3% of total irrigation water consumption, whereas low water- consuming crops contribute only 19.7%. Altogether, the combined water consumption of both groups amounted to 63,485.85 (mm) (Fig 2). This pronounced asymmetry indicates that even a limited reduction in the cultivation share of water-intensive crops could produce a disproportionately large decrease in total agricultural water consumption, compared with merely expanding the cultivation of low water- consuming crops. In other words, the optimal strategy is not simply the promotion of low water- consuming crops, but rather a combined approach involving the targeted restriction of the most water-intensive crops, particularly sugarcane (*Saccharum officinarum*) and alfalfa (*Medicago sativa*), alongside the gradual replacement of transitional crops through cropping pattern reform and improvements in irrigation efficiency. Such a dual strategy could provide the greatest effectiveness in alleviating pressure on both renewable and non-renewable water resources, while simultaneously preserving crop diversity and the economic value of the field sector.

The high water-consuming horticultural crops have substantially greater water consumption, more than twice that of high water-consuming field crops (Fig. 2). In contrast, low water-consuming field crops exhibit higher water consumption than low water-consuming horticultural crops. Overall, high water-consuming horticultural crops account for the largest share of the total water use. Thus, a highly distinct pattern was observed between high water-consuming and low water-consuming crops in both horticultural and field crop groups. The WRa index, as an indicator of real water use, revealed considerable differences among these groups, reflecting the varying levels of pressure imposed on water resources under different cropping systems.

In the horticulture sector, the total WRa index for high water-consuming crops was reported as 33656.1 (mm), whereas the corresponding value for low water-consuming crops was only 17342.9 (mm). This substantial difference indicates that high water-consuming horticultural crops consume approximately 2.6 times more water than low water-consuming orchards. Such variation is mainly attributed to high

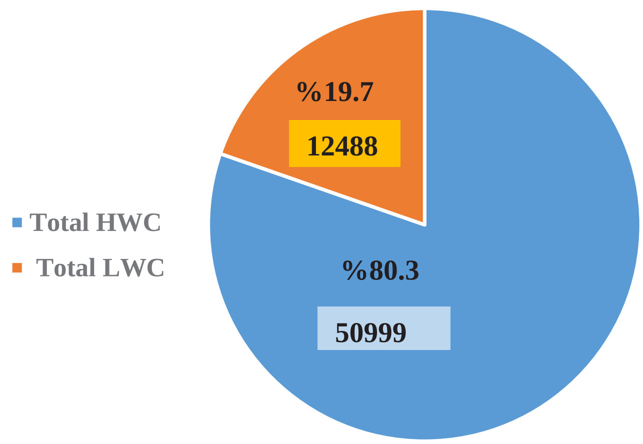


Fig. 1. Comparison of WRa between high water-consuming (HWC) and low water-consuming (LWC) crops

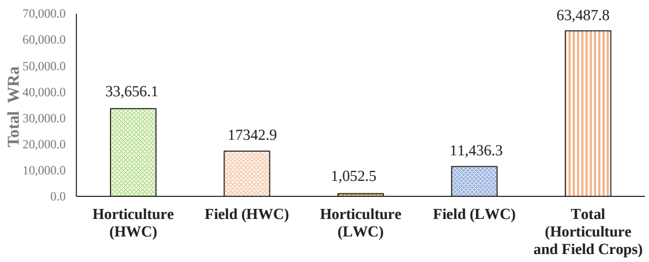


Fig. 2. Total WRa index of high and low water-consuming field and horticulture crops

water requirements of date palm (*Phoenix dactylifera*), papaya (*Carica papaya*), rice (*Oryza sativa*), and banana (*Musa acuminata*), which exhibited the highest WRa values (Table 1). In contrast, citrus, sesame (*Sesamum indicum*), sunflower (*Helianthus annuus*), and raspberry (*Rubus idaeus*) were categorized as low water-consuming crops (Table 2) and demonstrated significantly lower water demands. These findings indicate that the composition of horticultural cropping patterns has a direct impact on water withdrawal, replacing high water-consuming crops with low water-consuming species could play a significant role in sustainable water resource management. A similar trend was observed in field crops; however, magnitude of difference was even greater. The total WRa value for high water-consuming field crops was 11,436.3 (mm), compared with only 1,052.5 (mm) for low water-consuming field crops. In other words, high water-consuming field crops consume more than ten times the amount of water used by the low water-consuming group. This considerable gap highlights the high sensitivity of field sector to crop selection. Crops such as sugarcane (*Saccharum officinarum*), alfalfa (*Medicago sativa*), sugar beet (*Beta vulgaris*), and potato (*Solanum tuberosum*) exhibited the highest WRa values and therefore contributed most significantly to increased WRa, whereas low water-consuming crops such as canola (*Brassica napus*), lettuce (*Lactuca sativa*), celery (*Apium graveolens*), and carrot (*Daucus carota subsp. sativus*) required substantially less water. Overall, total WRa index for high water-consuming crops was markedly higher than that of low water-consuming crops, indicating that nearly 80% of total WRa is associated with high water-consuming crops (Fig. 1). This finding suggests that the current cropping pattern is highly dependent on crops with high water requirements. Under conditions of water scarcity and increasing pressure on water resources, maintaining such a pattern may seriously threaten the sustainability of the field sector.

The results of this study suggest that revising cropping patterns and promoting the cultivation of low water-consuming crops could be among the most effective strategies for reducing pressure on water resources. Furthermore, substantial differences observed between crop groups indicate that agricultural policies should be developed based on water productivity and WRa indices rather than solely on production performance. In practice, shifting toward crops with lower WRa values could help maintain agricultural production while simultaneously enhancing the resilience of agricultural systems to drought and climate change.

The findings of the present study WRa index are consistent with numerous studies reporting high water consumption in traditional horticultural and field crops, thereby supporting the validity of the graphical results. The HWC account for a substantially larger share of actual water consumption compared with LWC, such that total WRa in HWC group is considerably higher than that of LWC group (Fig. 2). This marked difference indicates that the current cropping pattern may impose significant pressure on water resources. Bekele (2025) emphasized that accurate estimation of crop water requirements is one of the fundamental pillars of sustainable water resource management and the design of optimal irrigation patterns. Accordingly, WRa index can serve as an effective tool for identifying crops with high water requirements and evaluating the sustainability of water use in field sector. Katerji and Mastrorilli (2014) stated that indices related to water use efficiency play a critical role in analyzing the performance of agricultural systems and optimizing water consumption, which is in agreement with the substantial differences observed between HWC and LWC crops in the present study.

The cropping pattern composition can directly contribute to reducing water consumption. Zou *et al.* (2018) reported that reducing the cultivated area of water-intensive crops and reforming cropping patterns in arid regions of China significantly decreased irrigation water demand. Likewise, Hao *et al.* (2018) demonstrated that optimizing cropping patterns based on water productivity can significantly reduce agricultural water consumption while maintaining economic profitability. Daccache *et al.* (2016) reported that replacing part of the high water-consuming crops with low water- consuming crops in the Mediterranean region resulted in the conservation of millions of cubic meters of water. Therefore, these findings suggest that incorporating the WRa index into cropping pattern planning can serve as an effective strategy for reducing pressure on water resources, improving water-use efficiency, and promoting sustainable agriculture, particularly in regions experiencing water scarcity and drought stress.

The study of the WRa index in plants is an important field within plant ecology and agricultural sciences that examines how different plant species utilize water resources. Its importance has increased significantly due to the intensifying global water scarcity caused by climate change, population growth, and rising agricultural demands (Brendel, 2021). Research in this field has evolved from early philosophical observations to advanced scientific investigations during the nineteenth and twentieth centuries, focusing on the complex physiological responses of plants to environmental conditions. Recent technological advances, including smart irrigation systems and artificial intelligence, have enabled real-time monitoring and optimization of water consumption, thereby enhancing agriculture resilience to climate change (Hatfield and Dold, 2019). Nevertheless, several challenges remain, including the lack of accurate datasets, environmental variability, and the need for localized assessments to adapt findings to different ecological conditions (Tercek *et al*., 2021). Overall, the study of plant water consumption indices not only improves our understanding of plant biology and ecology but also plays a critical role in the development of sustainable agricultural practices and policies aimed at conserving valuable water resources.

CONCLUSION

This study classified 83 field and horticulture crops in Iran into high and low water-consuming categories based on their actual water consumption (WRa) using a national dataset covering the period 2013–2023. The results revealed a pronounced imbalance in agricultural water use, with high water-consuming crops accounting for 80.3% of total WRa. Although several field crops, particularly sugarcane (*Saccharum officinarum*) and alfalfa (*Medicago sativa*), exhibited the highest individual WRa values, the horticultural sector emerged as the dominant contributor to agricultural water consumption because of the large number of water-intensive horticultural species. Among horticulture crops, papaya (*Carica papaya*), date palm (*Phoenix dactylifera*), banana (*Musa acuminata*), sapodilla (*Manilkara zapota*), and guava (*Psidium guajava*) showed the highest WRa values, reflecting the considerable water demand of tropical and subtropical species cultivated under Iran's arid and semi-arid conditions. Collectively, high water-consuming horticultural crops accounted for 72.3% of the total WRa within the high water-consuming category, highlighting the critical role of horticulture crop selection in national water-resource management. In contrast, crops such as kiwifruit (*Actinidia deliciosa*) and barberry (*Berberis vulgaris*) exhibited relatively low WRa values, indicating their potential as more water-efficient alternatives for future horticultural development.

The results also demonstrated that several strategic field crops, including wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and canola (*Brassica napus*), were classified within the low water-consuming category, suggesting that improvements in water security do not necessarily conflict with food-security objectives. Furthermore, crops with WRa values near the 600-mm threshold, including sesame (*Sesamum indicum*) and sunflower (*Helianthus annuus*), represent promising candidates for reducing agricultural water use through improved irrigation management and precision irrigation technologies. Overall, the findings indicate that sustainable agricultural water management in Iran should prioritize reforming horticulture cropping patterns while simultaneously improving irrigation efficiency in both horticulture and field crop systems. Restricting the expansion of highly water-intensive horticultural species, promoting low-WRa alternatives, and incorporating WRa-based criteria into agricultural planning can substantially reduce pressure on water resources and enhance the long-term sustainability of Iranian agriculture under increasing water scarcity and climate change.

REFERENCES

Ahmed, S. B., Alawad, B. M. H. and Saeed, A. B. 2024. Effect of Irrigation Quantity on Water Use Efficiency of Guar under New Halfa Condition, Sudan. *International Journal* **9**(5): 26–35.

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56. *FAO*, Rome 300(9): D05109.

Bayisa, G. D., Ayana, M., Mekonnen, B., Hordofa, T. and Dinka, M. O. 2024. Drainage Lysimeter Based Measurement of Water Requirement and Crop Coefficient of Bread Wheat under Semi-Arid Climate of Melkassa, Ethiopia. *Heliyon* **10**(17).

Bekele, T. T. 2025. Potato Production in Ethiopia: Challenges, Opportunities, and Strategies for Sustainable Growth.

Bijlwan, A., Pokhriyal, S., Ranjan, R., Singh, R. K. and Jha, A. 2024. Machine Learning Methods for Estimating Reference Evapotranspiration. *Journal of Agrometeorology* **26**(1): 63–68.

Boser, A., Caylor, K., Larsen, A., Pascolini-Campbell, M., Reager, J. T. and Carleton, T. 2024. Field-Scale Crop Water Consumption Estimates Reveal Potential Water Savings in California Agriculture. *Nature Communications* **15**(1): 2366.

Brendel, O. 2021. The Relationship between Plant Growth and Water Consumption: A History from the Classical Four Elements to Modern Stable Isotopes. *Annals of Forest Science* **78**: 47.

Chukalla, A. D., Mekonnen, M. M., Gunathilake, D., Wolkeba, F. T., Gunasekara, B. and Vanham, D. 2025. Global Spatially Explicit Crop Water Consumption Shows an Overall Increase of 9% for 46 Agricultural Crops from 2010 to 2020. *Nature Food* **6**(10): 983–994.

Daccache, A., D'Agostino, D., Lamaddalena, N. and El Chami, D. 2016. A Decision Tool for Sustainable Agricultural Policies: The Case of Water Saving Scenarios for Apulia Region (Southern Italy). *Water Policy* **18**(1): 126–42.

Ebrahimipak, N. A. and Sedaghat, A. 2025. An Analysis on Evaluation of Virtual Water Index of Horticultural and Field Crops Grown in Iran. *International Journal of Innovative Horticulture* **14**(2): 151–61.

Ebrahimipak, N., Sedaghat, A. and Tafteh, A. 2026. Spatial Analysis of Water Requirements and Water-Use Efficiency in Wheat Cultivation across Iran Using Data From the Water Requirement System. *Irrigation and Drainage*.

Fereres, E. and Soriano, M. A. 2007. Deficit Irrigation for Reducing Agricultural Water Use. *Journal of Experimental Botany* **58**(2): 147–59.

Fereres, E., Goldhamer, D. A. and Parsons, L. R. 2003. Irrigation Water Management of Horticultural Crops. *HortScience* **38**(5): 1036–42.

Gil-Marín, J. A., Zermeño-González, A., Córdova-Rodríguez, M. X., Ramírez-Rodríguez, H., Melendres-Alvarez, A. I., Moreno, L. S. and Khamkure, S. 2025. Evapotranspiration and the Crop Coefficients of Black Bean (*Phaseolus vulgaris* L.) with Weighing Lysimeters. *Asian Journal of Agriculture* **9**: 349–57.

Hao, L., Su, X. and Singh, V. P. 2018. Cropping Pattern Optimization Considering Uncertainty of Water Availability and Water Saving Potential. *International Journal of Agricultural and Biological Engineering* **11**(1): 178–86.

Hatfield, J. L. and Dold, C. 2019. Water-Use Efficiency: Advances and Challenges in a Changing Climate. *Frontiers in Plant Science* **10**: 103.

Ichwan, N., Meliala, F.S., Ezra, M.F., Nainggolan, M.B., Nasution, D.L.S. and Daulay, S.B. 2022. Water Consumption, Growth, Yield and Water Productivity for Pepper Plant. IOP Conference Series: Earth and Environmental Science **977**(1): 012076.

Karandish, F. and Hoekstra, A. Y. 2017. Informing National Food and Water Security Policy through Water Footprint Assessment: The Case of Iran. *Water* **9**(11): 831.

Karandish, F., Hoekstra, A. Y. and Hogeboom, R. J. 2018. Groundwater Saving and Quality Improvement by Reducing Water Footprints of Crops to Benchmarks Levels. *Advances in Water Resources* **121**: 480–91.

Katerji, N. and Mastrorilli, M. 2014. Water Use Efficiency of Cultivated Crops. *eLS*.

Kebede, N., Ayana, M. and Mekonnen, B. 2025. Quantification of Onion (*Allium cepa* L.) Evapotranspiration and Crop Coefficient via Weighable Lysimeter under Semi-Arid Climate of Melkasa, Ethiopia. *Heliyon* **11**(4).

Keyser-Gibson, A., Nackley, L., Sun, Y., Sisneroz, J., Haver, D., Contreras, R., Schuch, U.K., Oki, L. and Kim, S.H. 2025. Plasticity in Plant Hydraulic Traits: An Evaluation of a Common-Taxa Experiment Across a Climatic Gradient in the Western US. Plants, People, Planet.

Khajavigodellou, Y., Qi, J., Soltani, M., Zarrin, Z., Karimi, H. and Bakhshianlamouki, E. 2026. Optimization of Agricultural Systems Under Water-Energy-Food Nexus: A Framework for the Urmia Lake Basin. *Sustainability* **18**(2): 843.

Khorsandi, M., Omidi, T. and van Oel, P. 2023. Water-Related Limits to Growth for Agriculture in Iran. *Heliyon* 9(5).

Lamsal, G. and Marston, L. T. 2025. Monthly Crop Water Consumption of Irrigated Crops in the United States from 1981 to 2019. *Water Resources Research* 61(2): e2024WR038334.

Li, G., Ma, D., Zhao, C. and Li, H. 2023. The Effect of the Comprehensive Reform of Agricultural Water Prices on Farmers' Planting Structure in the Oasis–Desert Transition Zone—A Case Study of the Heihe River Basin. *International Journal of Environmental Research and Public Health* **20**(6): 4915.

Mirzaei, A., Saghafian, B., Mirchi, A. and Madani, K. 2019. The Groundwater–Energy–Food Nexus in Iran's Agricultural Sector: Implications for Water Security. *Water* **11**(9): 1835.

Negash, T. W., Dirirsa Bayisa, G., Tefera, A. T., Tezera Bizuneh, K., Dinku, A. G., Awulachew, T. W. and Ashemi Bikela, G. 2023. Evapotranspiration and Crop Coefficient of Sorghum (*Sorghum bicolor* L.) at Melkassa Farmland, Semi-Arid Area of Ethiopia. *Air, Soil and Water Research* 16: 11786221231184206.

Negash, T. W., Tefera, A. T. and Bayisa, G. D. 2024. Maize (*Zea mays* L., 1753.) Evapotranspiration and Crop Coefficient in Semi-Arid Region of Ethiopia. *Italian Journal of Agrometeorology* **2**: 55–63.

Preite, L., Solari, F. and Vignali, G. 2023. Technologies to Optimize the Water Consumption in Agriculture: A Systematic Review. *Sustainability* **15**(7): 5975.

Tercek, M. T., Thoma, D., Gross, J. E., Sherrill, K., Kagone, S. and Senay, G. 2021. Historical Changes in Plant Water Use and Need in the Continental United States. *PLOS ONE* **16**(9): e0256586.

Wong, A. J., Jin, Y., Medellín-Azuara, J., Paw U, K. T., Kent, E. R., Clay, J. M. and Hook, S. J. 2021. Multiscale Assessment of Agricultural Consumptive Water Use in California's Central Valley. *Water Resources Research* **57**(9): e2020WR028876.

Zamani, A., Rostamian, R. and Norouzi, G. 2024. Comparative Assessment of Environmental Impacts and Water Scarcity Footprint of Horticultural Crops in Iran. Environmental Research **257**: 119082.

Zou, M., Kang, S., Niu, J. and Lu, H. 2018. A New Technique to Estimate Regional Irrigation Water Demand and Driving Factor Effects Using an Improved SWAT Model with LMDI Factor Decomposition in an Arid Basin. *Journal of Cleaner Production* 185: 814–28.

Current Horticulture **14**(2): 68-70, April–June 2026
DOI: 10.5958/2455-7560.2026.00021.7
Received: 19 November 2025; Accepted: 04 April 2026

Morpho-biochemical characterization of jamun (*Syzygium cumini*) varieties for nutrition and livelihood security

Kanupriya Chaturvedi*, Arivalagan M, Sankaran M and Tripathi P C*

ICAR–Indian Institute of Horticultural Research, Bengaluru, Karnataka-560089, India

Abstract

Three farmers' varieties of jamun, *Syzygium cumini (*L.) Skeels., Patel Jumbo, Patel Samruddhi and Patel Akal, identified from Nagadasanahalli village (Bengaluru Rural district, Karnataka) were characterized morphologically and biochemically, following DUS descriptors by ICAR-IIHR, Bengaluru, during 2024-25. The varieties displayed distinctiveness in fruit weight (7.1–12.65 g), pulp colour (pinkish-white to purple), total soluble solids (10.79–14.02 °Brix), acidity, and anthocyanin content. Patel Jumbo exhibited the highest fruit weight and pulp sweetness, Patel Samruddhi showed unique purple pulp with high productivity, while Patel Akal extended the fruiting season into July–August. Morphological traits including fruit shape, size, and pulp characteristics showed clear divergence among all the varieties. Biochemical profiling confirmed variation in TSS, acidity, phenolics, and anthocyanins. The results provide scientific validation for their distinctiveness, uniformity, and stability (DUS) and support their suitability for PPV&FRA registration. The study highlights the value of farmer-led germplasm development for climate-resilient dryland horticulture.

Key words: Biochemical, Fruit weight, Farmers' varieties, Pulp colour, TSS

Jamun, *Syzygium cumini* (L.) Skeels., a member of the Myrtaceae family, is an underutilized yet highly valuable indigenous fruit species widely distributed across the Indian subcontinent. Its fruits are purple, fleshy, and seed-rich, and the volatile oils extracted from them are traditionally used to manage diabetes, cardiac ailments, and liver disorders (Vijayanand *et al.,* 2001; Singh, 2001). Owing to its medicinal attributes and utility as a windbreak species, demand for jamun has steadily increased, highlighting the need for high-yielding, superior-quality planting material. Despite its potential, systematic improvement in jamun remains limited. Most trees across India are of seedling origin, leading to considerable variability in morphology, reproductive behaviour, fruiting patterns, and physico-chemical properties (Tripathi *et al.,* 2025). This diversity is primarily a consequence of its sexual mode of reproduction and highly cross-pollinated nature. While such variation represents a rich resource for selection, it also underscores the need for structured evaluation to identify elite genotypes suited for horticultural expansion, processing industries, and pharmaceutical applications (Prakash *et al.,* 2010; Singh *et al.,* 2022).

For the formal recognition, protection, and dissemination of such elite material, scientific validation using Distinctiveness, Uniformity and Stability (DUS) descriptors is essential. Registration under the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA) provides legal acknowledgement, safeguards breeders' or farmers' rights, and supports wider adoption of improved germplasm. However, farmer-identified jamun types remain largely undocumented in scientific literature, limiting their integration into national germplasm repositories and breeding programmes. The present study addresses this gap by providing a comprehensive morpho-biochemical characterization of elite jamun varieties collected from Nagadasanahalli village, Bengaluru Rural district, Karnataka, India.

MATERIALS AND METHODS

Elite jamun trees, viz. Patel Jumbo, Patel Samruddhi and Patel Akal were evaluated during 2024-25 at ICAR-IIHR, Bengaluru. The trees (more than 12 years old) were selected and maintained under uniform field conditions without supplemental irrigation or external nutrient inputs. Morphological characterization was conducted following PPVFRA DUS guidelines. Ten fully mature fruits /tree were sampled, and observations were recorded for fruit weight (g), fruit length and width (cm), seed weight (g), pulp percentage (%), pulp and fruit colour, and fruit shape including apex and stalk-end characteristics. Measurements were taken using digital Vernier callipers, and colour attributes were assessed using the RHS colour chart. Biochemical analysis was carried out on fresh fruit samples to estimate total soluble solids (°Brix), titratable acidity (%), and anthocyanin content (mg/100 g). Total soluble solids were measured using

***Corresponding author :** prakaashtripathii2000@yahoo.co.in

Table 1: Qualitative characteristics of jamun genotypes

Genotype	Fruit shape	Pulp color	Taste and TSS	Special traits	Harvesting time
Patel Jumbo	Elliptical	Pinkish-white	Sweet, no astringency	Large size, high yield, premium market appeal	June (regular season)
Patel Samruddhi	Elliptical	Purple	Tangy, astringent	Heavy bearer, vibrant color for processing	June
Patel Akal	Oblong	Pinkish-white	Sweet-acidic, mild astringency	Late fruiting, extends jamun season	July–August
Dupdal	Oblong	Pinkish-white	Sweet, no astringency	premium market appeal	May-June

Table 2: Morphological characteristics of fruits from jamun genotypes

Genotype	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Fruit length:width	TSS (oBrix)	Seed width (mm)	Seed length (mm)	Pulp weight (g)	Pulp (%)
Patel Jumbo	12.65	2.99	2.13	1.40	14.02	1.21	1.65	11.31	89.41
Patel Samruddhi	7.1	2.08	1.13	1.84	10.79	1.02	1.41	6.05	85.21
Patel Akal	11.35	3.18	2.36	1.35	13.3	1.14	1.08	10.21	89.96
Dhupdal	12.76	3.26	2.05	1.59	16.83	0.96	2.08	10.6	83.09

Table 3: Biochemical characteristics of fruits from jamun genotypes

Genotype	Titratable acidity*(%)	Total sugars (g)	Reducing sugars (g)	Anthocyanin (mg C3GE)	Total phenolic content (mg GAE)	Total flavonoids content (mg CE)	FRAP (mg TE)	DPPH (mg TE)
Patel Jumbo	0.59	10.49	7.64	94.85	140.90	67.85	272.60	355.35
Patel Samruddhi	0.56	8.18	6.17	198.75	404.60	120.45	911.55	733.85
Patel Akal	0.65	8.08	5.82	107.60	244.90	78.25	534.55	524.50
Dhupdal	1.31	8.8	6.06	84.35	146.51	68.57	307.78	629.79

*Titratable acidity measured as % citric acid equivalent
DPPH and FRAP values are expressed as mg trolox equivalent/100 g pulp
C3GE – Cyanidin-3-glucoside Equivalent, GAE - Gallic Acid Equivalent, CE- Catechin Equivalent, TE- Trolox Equivalent

a portable hand refractometer, acidity was determined through standard titration procedures, and anthocyanin content was quantified using spectrophotometric methods as per protocols of AOAC, 2006.

RESULTS AND DISCUSSION

The jamun genotypes namely, Patel Jumbo, Patel Samruddhi, Patel Akal and the check Dhupdal showed clear morphological variation in fruit shape, pulp colour, taste, and harvesting time, consistent with broad diversity reported earlier (Singh *et al.,* 2020; Alam *et al.,* 2020). Fruit shape ranged from elliptical to oblong, while pulp pigmentation varied from purple in Patel Samruddhi to pinkish-white in the remaining genotypes, aligning with earlier observations that darker fruits tend to be less common but biochemically richer (Ghosh *et al.,* 2017; Verma *et al.,* 2019). Taste differences such as sweet (Patel Jumbo, Dhupdal), tangy-astringent (Patel Samruddhi), and sweet-acidic (Patel Akal) also matched the flavour diversity documented in previous evaluations (Patel *et al.,* 2005; Devi *et al.,* 2019). Harvest windows differed substantially, with Dhupdal ripening early and Patel Akal extending the season into July-August, supporting earlier conclusions on the value of late-fruiting genotypes for market continuity (Singh *et al.,* 2020).

Quantitative traits reinforced this differentiation. Fruit weight and size were highest in Dhupdal and Patel Jumbo, comparable to large-fruited types (Alam *et al.,*2020). The TSS ranged widely (10.79-16.83°Brix), reflecting genetic variability in sweetness (Agrawal *et al.,* 2017; Singh *et al.,* 2016). Pulp percentage was highest in Patel Akal and Patel Jumbo, echoing findings that high-pulp genotypes such as Konkan Bahadoli are preferred for processing (Patel *et al.,* 2005; Devi *et al.,* 2019). Seed traits, though less variable, aligned with previous reports highlighting their relevance for medicinal extraction due to high polyphenolic content (Ayyanar & Subash-Babu, 2012; Megha *et al.,* 2017).

Biochemical parameters showed the strongest discrimination among genotypes. Patel Samruddhi stood out with exceptionally high anthocyanins, phenolics, flavonoids, and antioxidant activity-values consistent with pigment-rich jamun types reported by Verma *et al.,* (2019), Talang *et al.,* (2017), and Suradkar *et al.,* (2017). Total phenolics in this genotype were 2-3 times higher than the check, comparable to the upper ranges previously reported in jamun and other antioxidant-rich fruits (Singh *et al.,* 2016; Megha *et al.,* 2017). Sugar composition followed expected patterns, with higher sugars in sweet genotypes and lower sugars in tangier types, consistent with earlier biochemical characterizations (Alam *et al.,* 2020). Dhupdal showed moderate antioxidant capacity and acidity, aligning with values typical of widely grown traditional cultivars (Shahnawaz and Sheikh, 2011).

The results highlight the functional complementarity of the evaluated genotypes. Patel Jumbo combines premium size, sweetness, and high pulp recovery; Patel Samruddhi is a nutraceutical-rich, pigment-dense genotype suited for functional foods and natural colourants; Patel Akal provides season extension and high pulp yield; and Dhupdal serves as a suitable check with stable but moderate biochemical attributes. The observed morphological and biochemical diversity, underscores the potential of elite selections for breeding programs focused on fruit quality, pigment enhancement, antioxidant capacity, and year-round supply within jamun value chains.

CONCLUSION

The documented distinctiveness and stability provide a scientific basis for germplasm registration, wider dissemination, and future breeding initiatives. By integrating farmer-led selection with formal characterization, this study supports the systematic promotion of elite jamun varieties with high nutritional value and strong economic potential.

REFERENCES

Agrawal, V., Rangare, N.R. and Nair, R. 2017. Variability studies in different accessions of jamun (*Syzygium cuminii* Skeels) from Madhya Pradesh. *International J. Chem. Stud.* **5**(3): 7-11.

Alam, M., Mani, A., Mitra, S. and Bauri, F.K. 2020. Flowering, fruiting and physico-chemical properties of jamun (*Syzygium cuminii* Skeels) grown in Nadia district of West Bengal. *Adv. Biores.* **11**(5): 1-5.

AOAC, Washington, DC. 2006. *Official Methods of Analysis* (18th edn). Association of Official Analytical Chemists, Washington.

Ayyanar, M. and Subash-Babu, P. 2012. *Syzygium cuminii* (L.) Skeels: Phytochemical constituents and traditional uses. *Asian Pac. J. Trop. Biomed.* **2(3)**: 240-46.

Devi, C.A., Sharma, G.L., Singh, P., Panigrahi, H.K., Sharma, H.G., Nag, J.L. and Paikra, P.S. 2019. Variability in fruit characters of jamun (*Syzygium cuminii*). *Pharma Innov. J.* **8**(9): 391-93.

Ghosh, P., Pradhan, R.C., Mishra, S., Pater, A.S. and Kar, A. 2017. Physicochemical and nutritional characterization of jamun. *Curr. Res. Nutr. Food Sci.* **5**(1): 25-35.

Megha, H., Ningot, E.P., Dahale, S., Bharad, G. and Nagre, P.K. 2017. Variability in physico-chemical characteristics of jamun genotypes from Eastern Maharashtra. *International J. Life Sci. Res.* **4**(1): 251-57.

Patel, V.B., Pandey, S.N., Singh, S.K. and Das, B. 2005. Variability in jamun (*Syzygium cuminii* Skeels) accessions from Uttar Pradesh and Jharkhand. *Indian J. Hort.* **62(3)**: 244-47.

Prakash, J., Maurya, A.N. and Singh, S.P. 2010. Variability in fruit characters of jamun. *Indian J. Hort.* **67**: 63-6.

Shahnawaz, M. and Sheikh, A.S. 2011. Physicochemical characteristics of jamun fruit. *J. Hort. For.* **3**(10): 301–306.

Singh, S. and Singh, A.K. 2012. Variability in jamun (*Syzygium cuminii* Skeels) from Gujarat. *Asian Journal of Horticulture* **7**(1): 186-89.

Singh, S.Y., Vivela, D.S. and Swamy, G.S.K. 2016. Genetic variation in morphological and physicochemical traits of jamun. *Asian Journal of Horticulture* **11**: 163-67.

Singh, S., Singh, S.P., Singh, V. and Shikha, K. 2020. Variability for fruit quality attributes in jamun genotypes. *Journal of Pharmacognosy and Phytochemistry* **9**(2): 617-20.

Singh, S., Singh, A. K., Mishra, D. S., Singh, G. P. and Sharma, B. D. 2022. Advances in research in jamun (*Syzygium cuminii*): a review. *Current Horticulture,* **10**(1): 8-14.

Suradkar, N.G., Pawar, V.S. and Shere, D.M. 2017. Physicochemical and bioactive composition of jamun fruit. *International Journal of Chemical Studies* **5**(3): 470-72.

Talang, H.D., Rekha, A., Dinesh, M.R. and Shivashankar, K.S. 2017. Physicochemical variability in selected jamun genotypes. *Indian Horticultural Journal* **7**(1): 64-6.

Tripathi, P.C., Sane, A., Ganesan, K., Vadivel, S., Kumar, P., Chaturvedi, K. and Thimmarayappa, R. 2025. Characterization of jamun (*Syzygium cumini* Skeels) accessions for economic traits based on multivariate analysis. *European Journal of Horticultural Science* **90**(1).

Verma, R.S., Lata, R., Ram, R.B., Prakash, S., Kumar, V., Verma, S.S., Pal, H. and Singh, R. 2019. Physicochemical attributes of jamun genotypes. *Journal of Pharmacognosy and Phytochemistry* **8**(5): 480-82.

Vijayanand, P., Rao, L.J.M. and Narsimhan, G. 2001. Volatile flavour components of jamun fruit. *Flavour and Fragrance Journal* **16**: 47-9.

Current Horticulture 14(2): 71-78, April–June 2026
DOI: 10.5958/2455-7560.2026.00022.3
Received: 21 May 2026; Accepted: 17 June 2026

Optimizing sweet pepper (*Capsicum annuum*) productivity and phytonutrient quality using photo selective shade nets under protected cultivation in Bangladesh

S.A. Sumona and A.H.M. Solaiman*
Department of Horticulture, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh

Abstract

An experiment was conducted on sweet pepper (*Capsicum annuum* L.) at the Horticulture Farm of Sher-e-Bangla Agricultural University, Dhaka, Bangladesh, during October 2019–April 2020 in a two-factor randomized complete block design with three replications. Factor A comprised three net environments: white net (CN, control net environment), green net (GN, 25% shade) and black net (BN, 40% shade). Factor B comprised three cultivars: F_1 hybrid 'Lalima' (R), 'Peperone Yolo Wonder' (G) and 'BARI Mistimorich 2' (Y). Thirty-day old seedlings were transplanted into 10 L polyethylene bags filled with a substrate mixture of soil, vermicompost, coco dust and mushroom compost in a 20:50:20:10 (v/v) ratio and placed inside walk in tunnels. Microclimate, growth, flowering, yield and fruit quality attributes were recorded and analyzed by analysis of variance, and treatment means were separated by LSD at $P \leq 0.05$. Net environment significantly affected plant growth, flowering, yield and fruit quality. GN produced the highest plant height, leaf number and leaf area, while BN resulted in inferior growth. Flowering was earliest and most profuse under GN, particularly in 'Lalima'. The GN × 'Lalima' combination recorded the highest fruit yield (34.52 t ha^{-1}). CN maintained the highest total soluble solids and vitamin C, whereas GN enhanced antioxidant activity and anthocyanin concentration. The results indicate that a moderate shade environment created by the green net improved sweet pepper performance under protected cultivation in Bangladesh.

Key words: Antioxidant activity, Colour shade net, Protected cultivation, Yield, Phytonutrient quality

Sweet pepper (*Capsicum annuum* var. *grossum* L., Solanaceae) is an economically important vegetable crop cultivated widely for its attractive fruit colour, flavour, nutritional value and market demand. The genus *Capsicum* includes about 20 species, of which five are domesticated and widely recognized, namely *C. annuum, C. frutescens, C. chinense, C. baccatum* and *C. pubescens* (Farris, 1988). Among these, *C. annuum* comprises a broad range of sweet and hot pepper types adapted to different agroclimatic conditions and consumer preferences. In Bangladesh, sweet pepper is commonly known as Capsicum and is still considered a minor vegetable crop, although its cultivation and consumption have been increasing, especially in urban and peri-urban markets (Hasanuzzaman, 1999; Paul, 2009). Recent work in Bangladesh has shown that protected structures such as net and net + polythene tunnels can improve growth, yield and profitability of sweet pepper compared with open-field cultivation, indicating considerable scope for expanding commercial production under controlled environments (Saha and Salam, 2004; Paul, 2009; Medany *et al.,* 2008; Ahmed *et al.*, 2016).

* **Corresponding author :** ahmsolaimanhort@sau.edu.bd

Despite its economic potential, sweet pepper is highly sensitive to environmental stresses, particularly high temperature and excessive solar radiation (Rylski and Spigelman, 1982; Bhatt *et al.,* 1992). Optimum temperature for growth and fruit set generally lies within a moderate range, whereas exposure to supra-optimal temperatures, especially high night temperature, can reduce pollen viability, impair fruit set and increase flower abscission (Rylski and Spigelman, 1982; Díaz-Pérez, 2014). Under Bangladesh conditions, high temperature, intense solar radiation, erratic humidity and pest pressure often constrain successful sweet pepper production, leading to poor fruit set, reduced yield and lower fruit quality.

Protected cultivation using shade nets or net houses has emerged as an effective strategy to regulate crop microclimate and improve crop performance under stress-prone environments (Shahak, 2008; Arthurs *et al.*, 2013). Photo-selective shade nets are particularly important because they not only reduce incident radiation but also alter the spectral composition and diffusion of light reaching the crop canopy. These changes can influence canopy temperature, leaf physiology, transpiration, flowering behaviour, fruit set and the accumulation of pigments and bioactive compounds in fruits (Iglesias and Alegre, 2006; Shahak, 2014; Ilic *et al.*, 2017). In addition, shade nets provide partial protection against wind, hail, birds and some insect-borne viral diseases, thereby contributing to more stable production (Shahak, 2008; Fallik *et al.*, 2009; Goren *et al.*, 2011).

A growing body of research has demonstrated that coloured or photo-selective nets can significantly affect yield and fruit quality of sweet pepper. Ilic *et al.* (2017) reported that coloured shade nets modified fruit structure, total soluble solids (TSS), vitamin C content and total yield of sweet pepper, with pearl and red nets creating favourable growing conditions under high-radiation environments. In Mediterranean and semi-arid regions, moderate shade levels improved plant water status, fruit yield and marketable quality of bell pepper compared with unshaded conditions (Díaz-Pérez, 2014; López-Marín *et al.,* 2012). Postharvest studies have further indicated that coloured nets such as pearl and yellow can reduce decay incidence and help maintain pepper quality during storage and shelf- life (Fallik *et al.*, 2009; Goren *et al.*, 2011; Selahle *et al.*, 2015). These findings suggest that both shade intensity and spectral properties of netting are important in determining crop response.

The response of sweet pepper to shade-net environments, however, is highly dependent on cultivar, season, local climate and net characteristics (Mashabela *et al.*, 2015; Milenković *et al.,* 2012). Information generated in Mediterranean or arid regions cannot be directly extrapolated to the humid subtropical conditions of Bangladesh, where temperature, humidity and radiation dynamics differ considerably. Although protected cultivation of sweet pepper is gaining interest in Bangladesh, location-specific information on the use of photo-selective shade nets for improving growth, yield and fruit quality remains limited. This gap justifies further evaluation of net environments under local production systems.Therefore, study was undertaken to evaluate the effects of different photo-selective shade net environments on growth, flowering, yield and fruit quality of sweet pepper under protected cultivation.

MATERIALS AND METHODS

The experiment was conducted at the Horticulture Farm of Sher-e-Bangla Agricultural University (SAU), Dhaka 1207, Bangladesh (23°74′ N, 90°35′ E; AEZ-28, Modhupur Tract) during October 2019 to April 2020. The soil was analyzed prior to transplanting at the SRDI Farmgate Laboratory, Dhaka. Treatments were laid out in a randomized complete block design with three replications in walk-in-tunnel structures (1.8 m × 3.0 m × 1.5 m). In the experiment, three separate coloured net houses were constructed, and each replication contained 27 plants, giving a total of 81 experimental plants. The experiment followed a two-factor factorial arrangement: Factor A consisted of three photo-selective shade nets—white net (CN, control net environment), green net (GN, 25% shade) and black net (BN, 40% shade) as specified by the manufacturer—while Factor B comprised three sweet pepper cultivars: F_1 hybrid 'Lalima' (R), 'Peperone Yolo Wonder' (G) and 'BARI Mistimorich 2' (Y).

Thirty-day-old seedlings were transplanted into cylindrical polyethylene grow bags of approximately 12 L capacity (25 cm diameter × 25 cm height). Each bag was filled with a pulverized substrate mixture of soil, vermicompost, coco dust and mushroom compost in a 20:50:20:10 (v/v) ratio and placed inside the corresponding tunnel under its designated shade net. Standard intercultural practices, including irrigation, staking, pruning and plant protection measures, were applied uniformly to all treatments in accordance with local recommendations for sweet pepper cultivation. Microclimate parameters inside the tunnels, including air temperature, relative humidity, UV irradiance, solar radiation, soil temperature and soil moisture, were recorded daily at 12:00 h. Temperature (°C) and relative humidity (%) were measured with a digital thermo-hygrometer; UV irradiance (mW cm^{-2}) with a UV light meter (SP-82UV, Lutron, USA); solar radiation (W m^{-2}) with a solarimeter (TM-201L, TENMARS Electronics Co. Ltd., Taiwan); soil temperature (°C) with a soil thermometer (HI145, Hanna Instruments, Romania); and soil moisture (%) with a portable soil moisture meter. Monthly means for each parameter were computed for the different shade nets and, where relevant, for shade net × cultivar combinations.

Growth, flowering and yield data were recorded from five randomly selected central plants per treatment in each replication, excluding border plants. Recorded growth parameters were plant height (cm), number of leaves $plant^{-1}$ and leaf area (cm^2). Reproductive and yield attributes included days to first flowering, days to 50% flowering, number of flowers $plant^{-1}$, number of fruits $plant^{-1}$, fruit length (cm), fruit diameter (cm), individual fruit weight (g), fruit yield $plant^{-1}$ (g) and total yield (t ha^{-1}). Harvesting of fruits started 80 days after transplanting (DAT) and continued up to the final harvest based on marketable fruit size and colour. Fruits were harvested manually in the morning by hand picking with an upward twist, leaving the fruit stalk attached. For fruit quality analysis, three market-mature fruits were randomly harvested from the sampled plants in each treatment per replication and pooled to form a composite sample for TSS, vitamin C, colour, antioxidant activity and anthocyanin determinations. TSS (°Brix) was measured in fruit juice using a digital refractometer. Vitamin C content was determined by the 2,4-dinitrophenylhydrazine (DNPH) colorimetric method after extraction in acidified solution and expressed as mg ascorbic acid 100 g^{-1} fresh weight (Hamner *et al.,* 1945). Fruit surface colour attributes (L*, a*, b*) were measured at two opposite equatorial positions on each fruit using a portable colour meter (3nh Technology Co., Ltd, China); Chroma was calculated. Antioxidant activity of methanolic extracts was evaluated using the DPPH radical scavenging assay and expressed as percentage inhibition of DPPH. Total monomeric anthocyanin content was determined by the pH-differential spectrophotometric method and expressed as mg cyanidin-3-glucoside equivalents 100 g^{-1} fresh weight.

All data were analyzed using Statistix 10 software. Analysis of variance appropriate for the factorial RCBD was performed, and treatment means were separated using the least significant difference (LSD) test at $P \leq 0.05$.

RESULTS AND DISCUSSION

Shade nets significantly altered the microclimate inside the tunnels, particularly air temperature, relative humidity and radiation. Maximum midday air temperature was generally highest under the white net (CN) and lowest under the black net (BN), whereas relative humidity showed the reverse trend. Solar radiation and UV irradiance were substantially reduced with increasing shade density, being greatest under CN and least under BN. Soil moisture was higher under shaded conditions, especially with greater shade intensity, indicating improved water conservation (Figs 1 and 2). These findings agree with earlier reports that photo-selective nets can reduce canopy temperature, increase relative humidity and decrease incident radiation, thereby creating a more favourable microclimate for horticultural crops (Ahmed *et al.*, 2016; Arthurs *et al.*, 2013; Shahak, 2008).The observed patterns support the interpretation that treatment response reflects a combined effect of net colour and shade intensity. Therefore, responses are discussed in terms of net environments or shade-net treatments rather than colour alone, except where spectral effects are specifically addressed.

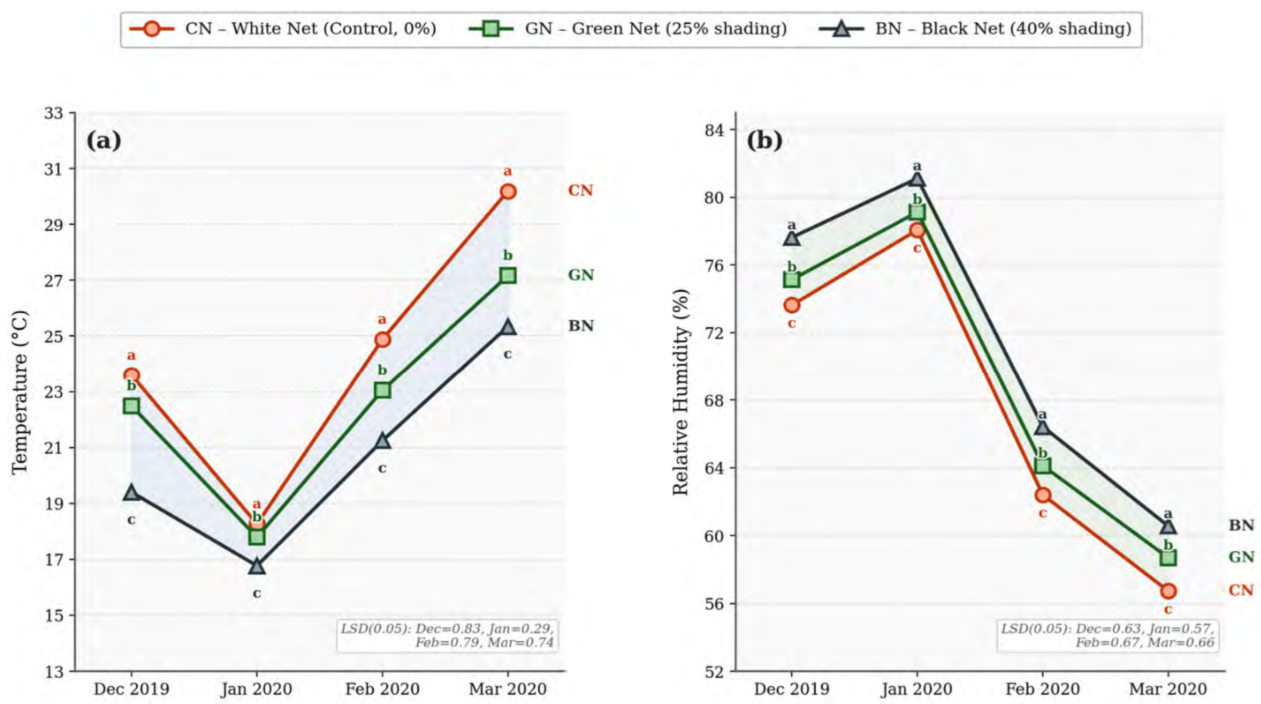


Fig. 1 : Mean (a) temperature (°C) (b) relative humidity (%) recorded at 12.00 noon under different color shade nets. Significance letters beside markers indicate LSD comparisons within each month ($P \leq 0.05$.). CN – White net (control); GN – Green net (25%); BN – Black net (40%). Within a column, means with the same letter(s) do not differ significantly at $P \leq 0.05$.

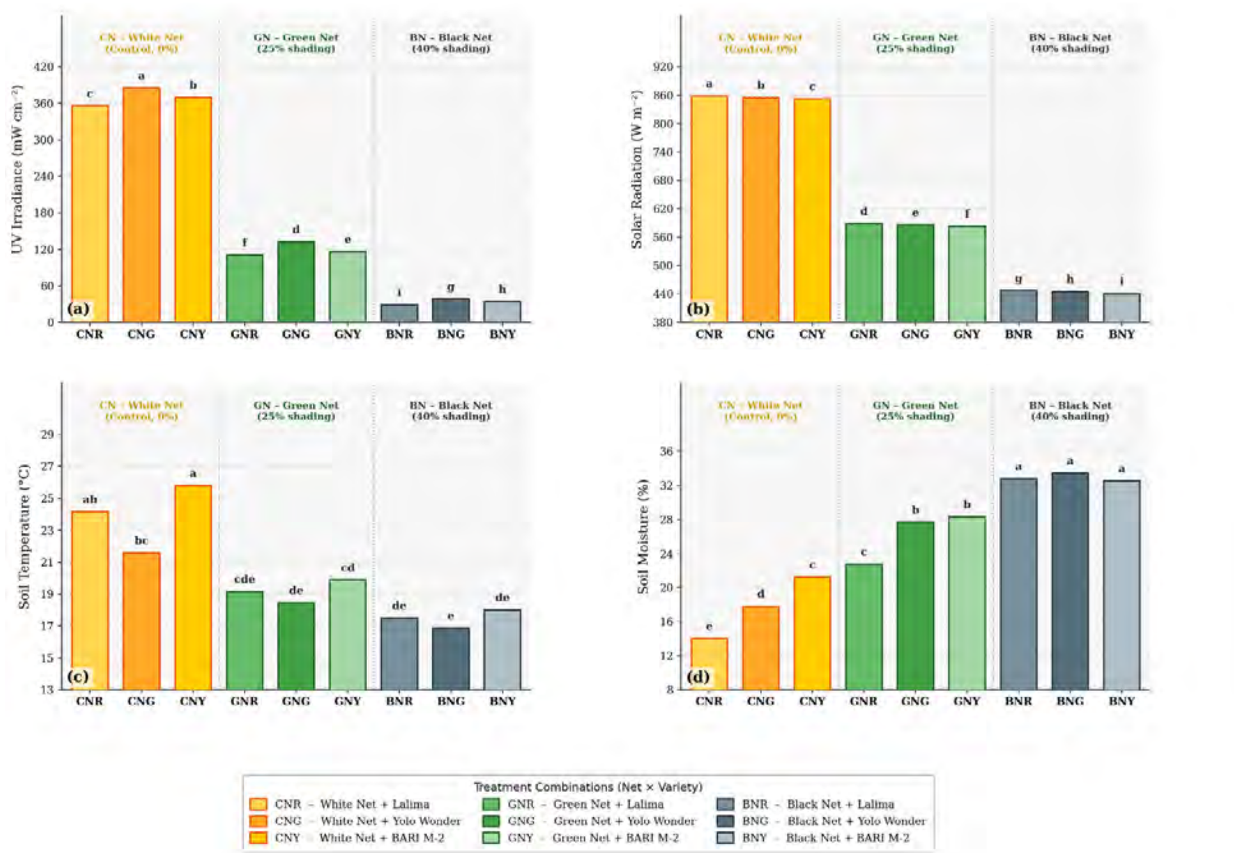


Fig. 2 : Fig. 2: (a) UV irradiance (mW cm^{-2}), (b) solar radiation (W m^{-2}), (c) soil temperature (°C), and (d) soil moisture (%) under different shade nets and varieties. CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid 'Lalima'; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

Growth attributes of sweet pepper were significantly influenced by shade net, cultivar and their interaction. Among the shade nets, GN produced the tallest plants, highest leaf number and greatest leaf area, whereas BN recorded the lowest values. The GNR combination (green net × 'Lalima') achieved the maximum plant height (75.17 cm), leaf number (54.83 $plant^{-1}$) and leaf area (305.33 cm^2), while BNG (black net × 'Peperone Yolo Wonder') consistently produced the poorest growth (Table 1). Enhanced vegetative growth under GN may be attributed to improved diffusion of photosynthetically active radiation and moderated temperature, which together favour canopy development compared with the high-radiation control (CN) or heavily shaded BN environment. Similar promotive effects of coloured shade nets on vegetative growth have been reported in other crops where light scattering and altered spectral composition increased light interception and photosynthesis (Nissim-Levi *et al.*, 2008; Appling, 2012; Milenković *et al.,* 2012).

Shade nets and cultivars significantly influenced fruit quality traits. TSS was highest under CN (9.08%) and in the CNR combination (10.23%), with values declining as shade intensity increased and reaching a minimum under BNG (3.80%). This inverse relationship between shading and TSS has been documented for sweet pepper and other horticultural crops, reflecting reduced sugar accumulation under lower light (Rylski and Spigelman, 1986; Díaz-Pérez, 2014). Colourimetric analysis indicated that GNR fruits exhibited the greatest redness (a*), whereas GNY (green net × 'BARI Mistimorich 2') recorded the highest lightness (L*) and yellow chromaticity (b* and Chroma), while BNR showed the lowest L* values (Table 2). These patterns suggest that green nets favour the accumulation of carotenoids and anthocyanins in red-fruited cultivars, in line with previous observations on the influence of modified light quality on pigment biosynthesis (Zhang *et al.*, 2014; Ilic *et al.*, 2017).

Table 1. Effect of color shade nets and varieties on growth parameters

Treatment	Plant height (cm)	Leaf number plant^{-1}	Leaf area (cm^2)	Days to 1st flower	Days to 50% flower	Flowers plant^{-1}
Effect of color nets						
CN	66.50 b	41.89 b	213.39 b	56.00 b	91.44 b	12.33 b
GN	73.89 a	50.01 a	270.42 a	46.22 c	82.11 c	15.33 a
BN	52.50 c	32.78 c	109.17 c	83.56 a	118.00 a	9.67 c
LSD0.05	0.76	0.99	19.06	1.31	1.17	0.89
CV (%)	1.19	2.37	9.65	2.12	1.20	7.15
Effect of varieties						
R	65.50 a	44.89 a	227.28 a	59.89 c	95.44 c	13.78 a
G	63.11 c	38.46 c	171.78 c	64.22 a	99.11 a	11.00 c
Y	64.28 b	41.33 b	193.92 b	61.67 b	97.00 b	12.56 b
LSD0.05	0.76	0.99	19.06	1.31	1.17	0.89
CV (%)	1.19	2.37	9.65	2.12	1.20	7.15
Combined effect						
CNR	67.50 c	44.67 c	249.17 bc	54.00 d	89.67 d	13.33 c
CNG	65.50 d	38.52 e	194.33 d	58.00 c	93.33 c	11.00 d
CNY	66.50 cd	42.50 d	196.67 d	56.00 cd	91.33 cd	12.67 c
GNR	75.17 a	54.83 a	305.33 a	44.67 f	80.67 f	17.00 a
GNG	72.67 b	46.35 c	232.33 c	48.00 e	83.67 e	14.00 bc
GNY	73.83 b	48.83 b	273.59 ab	46.00 ef	82.00 ef	15.00 b
BNR	53.83 e	35.17 f	127.33 e	81.00 b	116.00 b	11.00 d
BNG	51.17 g	30.50 h	88.67 f	86.67 a	120.33 a	8.00 e
BNY	52.50 f	32.67 g	111.50 ef	83.00 b	117.67 b	10.00 d
LSD0.05	1.32	1.71	33.02	2.27	2.03	1.54
CV (%)	1.19	2.37	9.65	2.12	1.20	7.15

CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid 'Lalima'; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

Table 2. Effect of color shade nets and varieties on yield parameters and total soluble solids

Treatment	Fruits plant^{-1}	Fruit length (cm)	Fruit diam. (cm)	Fruit wt. (g)	Yield plant^{-1} (g)	Yield (t ha^{-1})	TSS (%)
Effect of color nets							
CN	4.36 b	6.64 b	5.40 b	47.97 b	209.37 b	22.76 b	9.08 a
GN	5.51 a	8.55 a	6.92 a	50.39 a	278.11 a	30.23 a	7.14 b
BN	3.22 c	5.70 c	4.67 c	46.34 c	149.62 c	16.26 c	5.01 c
LSD0.05	0.34	0.33	0.08	0.44	16.83	1.83	0.29
CV (%)	7.83	4.80	1.44	0.91	7.93	7.93	4.13
Effect of varieties							
R	4.86 a	7.64 a	6.00 a	49.08 a	240.48 a	26.14 a	7.98 a
G	3.95 c	6.30 c	5.37 c	47.29 c	188.54 c	20.49 c	6.22 c
Y	4.28 b	6.95 b	5.62 b	48.33 b	208.08 b	22.62 b	7.03 b
LSD0.05	0.34	0.33	0.08	0.74	16.83	1.83	0.29
CV (%)	7.83	4.80	1.44	0.91	7.93	7.93	4.13
Combined effect							
CNR	4.75 bc	7.13 cd	5.70 d	48.58 cd	230.85 cd	25.09 cd	10.23 a
CNG	4.08 d	6.20 ef	5.10 f	47.33 ef	193.25 ef	21.01 ef	8.23 c
CNY	4.25 cd	6.60 de	5.40 e	48.00 de	203.99 de	22.17 de	8.77 b
GNR	6.17 a	9.88 a	7.40 a	51.50 a	317.58 a	34.52 a	7.60 d
GNG	5.12 b	7.23 c	6.57 c	49.17 c	251.59 bc	27.35 bc	6.63 e
GNY	5.15 b	8.53 b	6.80 b	50.50 b	265.17 b	28.82 b	7.20 d
BNR	3.67 de	5.90 fg	4.90 g	47.17 fg	173.00 fg	18.80 fg	6.10 f
BNG	2.67 f	5.47 g	4.43 i	45.37 h	120.77 h	13.13 h	3.80 h
BNY	3.33 e	5.73 fg	4.67 h	46.50 g	155.08 g	16.86 g	5.13 g
LSD0.05	0.59	0.56	0.14	0.76	29.15	3.17	0.50
CV (%)	7.83	4.80	1.44	0.91	7.93	7.93	4.13

CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid 'Lalima'; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

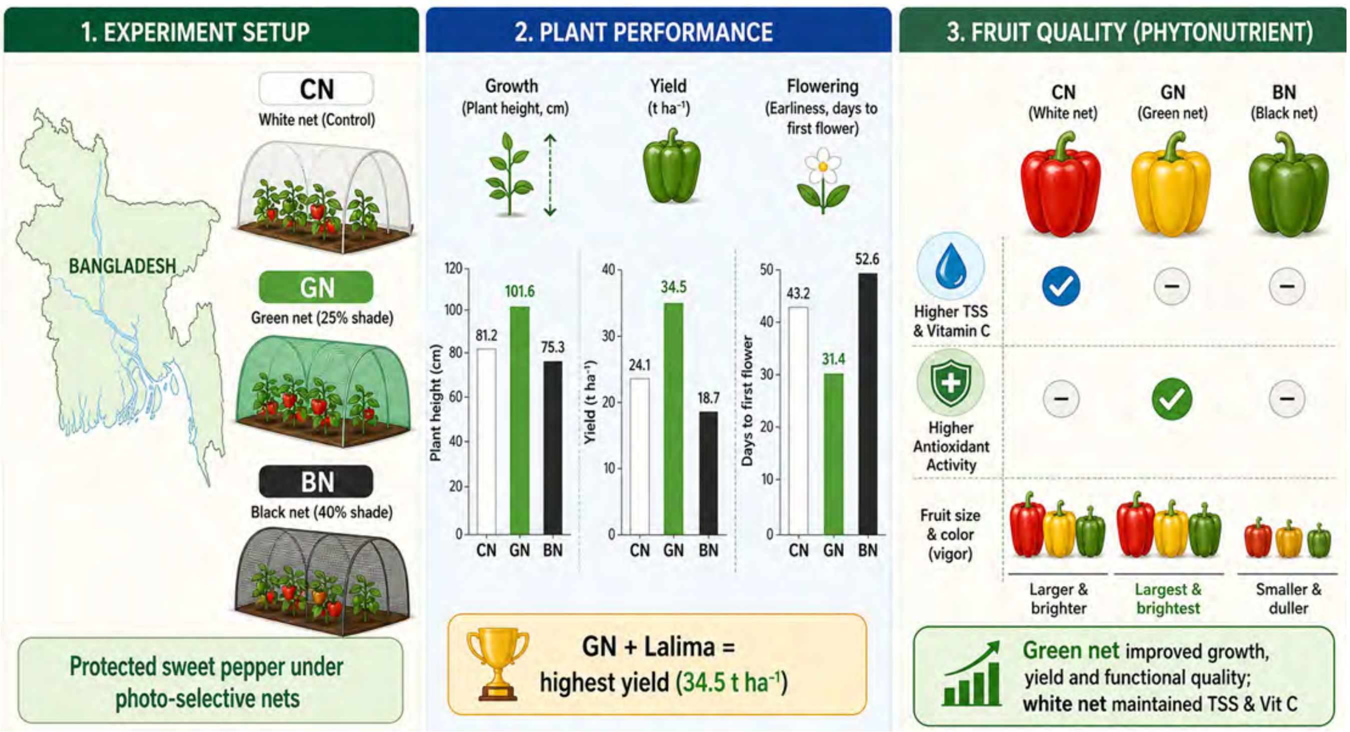
Vitamin C content was highest under CN and in the CNG combination and lowest in BNY, indicating that ascorbic acid biosynthesis benefited from higher light intensity, consistent with earlier findings in tomato and pepper (Hamner *et al.*, 1945; Mashabela *et al.*, 2015). In contrast, antioxidant activity and anthocyanin concentration were greatest under GN (78.80%; 7.71 mg 100 g^{-1} FW) and in GNR (81.16%; 10.47 mg 100 g^{-1} FW), and lowest under BN and BNG (Table 3). The selective enhancement of antioxidant compounds by green nets, despite moderate shading, may reflect wavelength-specific stimulation of flavonoid biosynthetic pathways, conferring improved health-promoting value to fruits harvested from GNR plots (Zhang *et al.,* 2014; Mashabela *et al.,* 2015; Selahle *et al.,* 2015).

Table 3. Effects of different color shade nets on fruit quality parameters of capsicum: fruit colorimetry (L*, a*, b*, Chroma), vitamin C content (mg 100 g^{-1} FW), antioxidant activity (%); and anthocyanin concentration (mg 100 g^{-1} FW).

Treatment	L*	a*	b*	Chroma	Vit. C (mg 100 g^{-1} FW)	Antioxidant (%)	Anthocyanin (mg 100 g^{-1} FW)
CNR	35.83 g	35.17 b	21.03 g	40.98 e	163.17 b	75.82 cd	9.17 b
CNG	38.83 e	7.92 gh	25.15 e	26.37 h	164.50 a	74.37 de	4.97 f
CNY	61.35 b	15.57 e	57.55 b	59.62 b	162.00 b	75.00 d	6.90 d
GNR	37.37 f	37.10 a	21.50 g	42.88 d	157.50 d	81.16 a	10.47 a
GNG	41.06 d	8.51 g	26.80 d	28.12 g	159.30 c	76.75 c	5.40 ef
GNY	63.28 a	17.36 d	69.01 a	71.16 a	156.00 e	78.48 b	7.27 d
BNR	34.57 h	33.06 c	18.63 h	37.96 f	148.83 f	73.43 ef	8.23 c
BNG	37.62 f	7.42 h	23.66 f	24.80 i	149.50 f	71.75 g	4.23 g
BNY	52.86 c	10.55 f	54.73 c	55.76 c	146.63 g	72.63 fg	5.73 e
CV (%)	1.37	3.12	1.06	1.05	0.44	1.12	4.65
LSD(0.05)	1.06	1.05	0.65	0.78	1.20	1.47	0.56

CN – White net; GN – Green net; BN – Black net; R – F_1 Hybrid 'Lalima'; G – Peperone Yolo Wonder; Y – BARI Mistimorich 2. Means with the same letter(s) do not differ significantly at $P \leq 0.05$.

Harnessing Photo-Selective Color Shade Nets to Improve Flowering, Yield and Postharvest Quality of Capsicum In Protected Cultivation



CONCLUSION

Photo-selective shade nets significantly modified the microclimate, growth, yield and fruit quality of sweet pepper under protected cultivation in Bangladesh. Among the treatments, the green net (25% shading) combined with F_1 hybrid 'Lalima' (GNR) consistently produced superior vegetative growth, earliest and most profuse flowering, highest fruit yield (34.52 t ha^{-1}) and enhanced antioxidant activity and anthocyanin content. White net treatments maintained higher TSS and vitamin C but were inferior to GNR in overall agronomic and biochemical performance. The study demonstrates that moderate green shading together with a suitable red-fruited hybrid is a promising technology package for commercial sweet pepper production in protected environments in Bangladesh and similar subtropical conditions. Validation across seasons and locations is, however, recommended before large-scale adoption.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the facilities and support provided by the Department of Horticulture, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh.

Conflict of interest

The authors declare no conflict of interest.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Author contributions

Conceptualization: A.H.M. Solaiman; Methodology: A.H.M. Solaiman, S.A. Sumona; Investigation: S.A. Sumona; Data curation: S.A. Sumona; Formal analysis: S.A. Sumona; Supervision: A.H.M. Solaiman; Visualization: S.A. Sumona; Writing – original draft: S.A. Sumona; Writing – review and editing: A.H.M. Solaiman. All authors have read and approved the final manuscript.

REFERENCES

Ahmed HA, Al-Faraj AA and Abdel-Ghany AM. 2016. Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review. *Sci. Hortic.* **201**:36–45.

Alkalai-Tuvia S, Goren A, Perzelan Y, Weinberg T and Fallik E. 2014. The influence of colored shade nets on pepper quality after harvest. *Agric. For.* **60**:7–18.

Ambrozy ZS, Daood H, Nagy ZS and Ledo H D. 2016. Effect of net shading technology and harvest times on yield and fruit quality of sweet pepper. *Appl. Ecol. Environ. Res.* **14**(1):99–109.

Appling S M. 2012. 'Colored shade affects the growth of basil, cilantro and parsley'. M.Sc. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

Arthurs S P, Stamps R H and Giglia F F. 2013. Environmental modification inside photo-selective shade houses. *HortScience* **48**:975–79.

Bhatt RM, Rao NKS and Anand N. 1992. Response of bell pepper to irradiance: Photosynthesis, reproductive attributes and yield. *Indian J. Horticulture* **56**(1):62–66.

Diaz-Perez JC. 2014. Bell pepper (*Capsicum annuum* L.) crop as affected by shade level: Fruit yield, quality, and postharvest attributes, and incidence of Phytophthora blight. *HortScience* **49**:891–900.

Fallik E, Alkalai-Tuvia S, Parselan Y, Aharon Z, Elmann A, Offir Y, Matan E, Yehezkel H, Ratner K, Zur N and Shahak Y. 2009. Can colored shade nets maintain sweet pepper quality during storage and marketing? *Acta Horticulturae* **830**:37–44.

Farris N P. 1988. *Perfect Peppers*. Horticultural Limited Partnership, USA, pp. 60–62.

Goren A, Alkalai-Tuvia S, Perzelan Y, Aharon Z and Fallik E. 2011. Photo-selective shade nets reduce postharvest decay development in pepper fruits. *Adv. Hort. Sci.* **25**(1):26–31.

Hamner KC, Bernstein L and Maynard LA. 1945. Effects of light intensity, day length, temperature, and other environmental factors on the ascorbic acid content of tomatoes. *J. Nutr.* **29**:85–97.

Hasanuzzaman S M. 1999. 'Effect of hormone on yield of bell pepper (Capsicum annuum L.)'. M.S. Thesis, Bangladesh Agricultural University, Mymensingh, Bangladesh.

Iglesias I and Alegre S. 2006. The effect of anti-hail nets on fruit protection, radiation, temperature, quality and profitability of 'Mondial Gala' apples. *J. Appl. Hortic.* **8**(2):91–100.

Ilic ZS, Milenkovic L, Sunic L, Barac S, Mastilovic J, Kevresan Z and Fallik E. 2017. Effect of shading by coloured nets on yield and fruit quality of sweet pepper. *Zemdirbyste-Agriculture* **104**(1):53–62.

Kong Y, Avraham L, Perzelan Y, Alkalai-Tuvia S, Ratner K, Shahak Y and Fallik E. 2013. Pearl netting affects postharvest quality of fruit in 'Vergasa' sweet pepper via light environment manipulation. *Sci. Hortic.* **150**:290–98.

Lopez-Marin J, Galvez A and Gonzalez A. 2012. Effect of shade on yield, quality and photosynthesis-related parameters of sweet pepper plants. *Acta*

Horticulturae **956**:545–52.

Mashabela N M, Selahle M K, Soundy P, Crosby M K and Sivakumar D. 2015. Bioactive compounds and fruit quality of green sweet pepper grown under different coloured shade netting during postharvest storage. *J. Food Sci.* **80**(11):C2612–C2618.

Medany M A, Hassanei M K and Farag A. 2008. Effect of black and white net as alternative covers to sweet pepper production under greenhouse in Egypt. *Acta Horticulturae* **807**:121–26.

Milenkovic L, Ilic ZS, Durovka M, Kapoulas N, Mirecki N and Fallik E. 2012. Yield and pepper quality as affected by light intensity using colour shade nets. *Agric. For.* **58**(1):19–33.

Nissim-Levi A, Farkash L, Hamburger D, Ovadia R, Forrer I, Kagan S and Oren-Shamir M. 2008. Light-scattering shade net increases branching and flowering in ornamental pot plants. *J. Hortic. Sci. Biotechnol.* **83**(1):9–14.

Paul T K. 2009. 'Technology of sweet pepper production in Bangladesh'. Ph.D. Thesis, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Salna, Gazipur, Bangladesh.

Rylski I and Spigelman M. 1982. Effects of different diurnal temperature combinations on fruit set of sweet pepper. *Sci. Hortic.* **17**:359–66.

Rylski I and Spigelman M. 1986. Effect of shading on plant development, yield and fruit quality of sweet pepper grown under conditions of high temperature and radiation. *Sci. Hortic.* **29**:31–35.

Saha S R and Salam M A. 2004. *Modern Techniques of Sweet Pepper Cultivation*. HRC, BARI, Gazipur, Bangladesh.

Selahle KM, Sivakumar D, Jifon J and Soundy P. 2015. Postharvest responses of red and yellow sweet peppers grown under photoselective nets. *Food Chem.* **173**:951–56.

Shahak Y. 2008. Photoselective netting for improved performance of horticultural crops. *Acta Hortic.* **770**:161–68.

Shahak Y. 2014. Photo-selective netting: An overview of the concept, research and development and practical implementation in agriculture. *Acta Hortic.* **1015**:155–62.

Shahak Y, Ratner K, Zur N, Offir Y, Matan E, Yehezkel H, Messika Y, Posalski I and Ben-Yakir D. 2009. Photo-selective netting: An emerging approach in protected agriculture. *Acta Hortic.* **807**:79–84.

Zhang Y, Butelli E and Martin C. 2014. Engineering anthocyanin biosynthesis in plants. *Curr. Opin. Plant Biol.* **19**:81–90.

Current Horticulture **14**(2): 79-83, April–June 2026
DOI: 10.5958/2455-7560.2026.00023.X
Received: 13 May 2026; Accepted: 17 June 2026

Effect of drip irrigation and fertigation on yield, water-and fertilizer-use efficiency and economics of greater yam *(Dioscorea alata)* in eastern India

M Nedunchezhiyan*, S K Jata, R Arutselvan and K Pati

Regional Centre, ICAR-Central Tuber Crops Research Institute, Bhubaneswar - 751 019, Odisha, India

Abstract

An experiment was conducted to see the effect of drip irrigation and fertigation on greater yam (*Dioscorea alata* L.) during 2020-21, 2021-22 and 2022-23 at the Regional Centre of ICAR-Central Tuber Crops Research Institute, Bhubaneswar, Odisha, in split plot design with drip irrigation levels in main plots (I_1-60% CPE, I_2-80% CPE and I_3-100% CPE) and in sub-plots fertigation levels (F_1- N- P_2O_5-K_2O 60-60-60 kg ha^{-1}, F_2- N- P_2O_5-K_2O 80-60-80 kg ha^{-1} and F_3- N- P_2O_5-K_2O 100-60-100 kg ha^{-1}). Check: (surface irrigation IW/CPE: 1.0; P_2O_5 60 kg ha^{-1} basal application; N-K_2O 80-80 kg ha^{-1} soil application at basal (40%), 30 (30%) and 60 (30%) days after planting) and control: (surface irrigation IW/CPE: 1.0; no fertilizer) also included to compare the treatments. The treatment I_3 resulted in higher tuber yield, cost of cultivation, gross return, net return and B:C ratio, however, it was statistically on a par with I_2. Among fertigation, treatment F_3 resulted in significantly higher tuber yield, cost of cultivation, gross return, net return and B:C ratio. The interaction treatment I_3F_3 resulted in higher tuber yield, gross and net returns as well as B:C ratio and it was statistically on a par with I_2F_3 and I_3F_2. The treatment I_2F_3 resulted in higher water-use efficiency (WUE) and fertilizer-use efficiency (FUE). Hence, treatment I_2F_3 can be recommended for optimum tuber yield, higher WUE and FUE and better returns.

Key words: Greater yam, Drip irrigation, Fertigation, Water-use efficiency, Eastern India

Greater yam (*Dioscorea alata* L.) serves as a staple food in many countries in Africa, Asia and South as well as Latin America. In India, yams are grown in an area of about 30,000 hectares, producing 8.10 lakh tonnes annually with a yield of 28 tonnes/ha. It is mostly cultivated in Kerala, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, Uttar Pradesh, Odisha, Gujarat and in North-eastern states (Nedunchezhiyan *et al*., 2023a). Greater yam is a subsistence food crop in tribal, hilly areas and in other parts, it is a vegetable cash crop (Nedunchezhiyan and Sahoo, 2019; Nedunchezhiyan *et al*., 2022). Greater yam is rich in starch, various minerals and dietary fibre which confers many health attributes to it (Vashi *et al*., 2018; Adomeniene and Venskutonis, 2022; Sinnadorai *et al*., 2022).

Greater yam, being a long duration (10 months) crop, can suffer from insufficient moisture during post monsoon. The most common method of irrigation is surface irrigation to cope up with the deficiency of rains. Although it ensures uniform spreading which causes high evaporation and seepage losses. Water is a scarce resource which needs to be preserved and the ultimate goal should be to ensure more crop per drop. Drip irrigation is an efficient method of providing water directly in to the root zone of the plants. The available research results revealed that the productivity gain due to drip method of irrigation was estimated to be in the range of 20 to 90% for different crops besides substantial saving of water to the extent of 40-80% (Sivanappan, 2004; Nedunchezhiyan *et al*., 2017). The greater crop yields with considerable saving of water and higher water use efficiency in vegetables was reported in drip irrigation systems (Manjunath *et al*., 2001; Tiwari *et al*., 2003). Schedule of irrigation by pan evaporation is an easy and inexpensive method and most widely adopted (Ertek *et al*., 2007). Further, surface irrigation becomes cumbersome at later stages [6 months after planting (MAP)] due to trailing of greater yam on the ground or stake. Under such situations, drip irrigation could be a better option for greater yam. In greater yam+maize (*Zea mays* L.) intercropping system drip irrigation at 100% of cumulative pan evaporation (CPE) during 1-90 DAP + at 80% of CPE during 91-270 DAP was found optimum for higher greater yam tuber yield (Nedunchezhiyan *et al*., 2020; Nedunchezhiyan *et al*., 2021).

The method of nutrient application is also important in improving the nutrient-use efficiency. Fertilizers applied directly to soil are generally not utilized efficiently by the crops. In fertigation, nutrients are applied through drip emitters directly into the zone of maximum root activity so as to achieve maximum yield (Patel and Rajput, 2000; Chawla and Narda, 2002). Intercultural operations such as surface irrigation and top dressing of fertilizers are very difficult due to huge canopy development after third month. Hence, drip irrigation and fertigation are right option for water and nutrient management for greater yam. Drip fertigation is considered to be most efficient in improving the yield (Behera *et al*., 2013). Nedunchezhiyan *et al*. (2018) reported higher fertilizer-use efficiency under drip fertigation in elephant-foot

Corresponding author : mnedun@gmail.com

yam (*Amorphophallus paeoniifolius* (Dennst.) Nicolson). Fertigation of 140-90-140 kg ha^{-1}of N-P_2O_5-K_2O was considered optimum for greater yam+maize intercropping system (Nedunchezhiyan *et al.*, 2021). Keeping in view, the study was carried out to find the effect of drip irrigation and fertigation on tuber yield, water-and fertilizer-use efficiency and economics of greater yam.

MATERIALS AND METHODS

A field experiment was conducted during 2020-21, 2021-22 and 2022-23 at the Regional Centre of ICAR-Central Tuber Crops Research Institute, Bhubaneswar, Odisha (20°14′53.25″ N, 85°47′25.85″ E; 33 M above MSL). The soil of experimental site (0-30 cm depth) had a pH of 6.4, soil organic carbon 0.39%, available nitrogen 218 kg ha^{-1}, available phosphorus 42.6 kg ha^{-1} and available potassium 358 kg ha^{-1}.

The climate of the experimental location is characterized by hot and humid summers and cool, dry winters. The mean weather data over the three experimental years showed that the average maximum and minimum temperatures during crop growing season were 32.4°C and 22.8°C, respectively. The average relative humidity was 79.8%. The total rainfall received during the crop growing period was 1288.4 mm with 82 rainy days. The total evaporation was 957.7 mm.

The experiment was laid out in split plot design with drip irrigation levels in main plots (I_1-60% CPE, I_2-80% CPE and I_3-100% CPE) and in sub-plots fertigation levels (F_1- N- P_2O_5-K_2O 60-60-60 kg ha^{-1}, F_2- N- P_2O_5-K_2O 80-60-80 kg ha^{-1} and F_3- N- P_2O_5-K_2O 100-60-100 kg ha^{-1}). Check: (surface irrigation IW/CPE: 1.0; P_2O_5 60 kg ha^{-1} basal application; N-K_2O 80-80 kg ha^{-1} soil application at basal (40%), 30 (30%) and 60 (30%) days after planting) and control: (surface irrigation IW/CPE: 1.0; no fertilizer) also included to compare the treatments. The treatments were replicated thrice. In fertigation treatments, water-soluble fertilizer N-P_2O_5-K_2O through fertigation as per treatment at basal (40%), 30 (30%) and 60 (30%) days after planting (DAP). In control/check, P_2O_5 was applied during last plough. N and K were applied in 3 splits at basal (40%), 30 DAP (30%) and 60 DAP (30%). Farmyard manure 10 t/ha was incorporated at last plough in all treatments except control/check. The cut tubers weighing 200 g were planted on ridge formed at 90 cm spacing. The plant- to -plant distance of 90 cm was maintained. The crop was harvested 300 days after planting.

The data were subjected to analysis of variance (ANOVA) appropriate for a randomized block design. Since the experiment was conducted over three consecutive years, a pooled analysis across years was performed. Treatment means were compared using the critical difference (CD) test at the 5% probability level following the procedures described by Panse and Sukhatme (1985).

RESULTS AND DISCUSSION

The results revealed that increasing irrigation level increased greater yam tuber yield (Fig. 1). The treatment I_3 resulted in higher tuber yield however, it was statistically on par with I_2. This showed that for drought resistant greater yam drip irrigation at 80% CPE was enough for getting optimum tuber yield. Nedunchezhiyan *et al.* (2021) reported that drip irrigation at 80% of CPE during 91-270 DAP (later part of crop growth stage) was found optimum for higher greater yam tuber yield in greater yam+maize intercropping system. When maize is intercropped with greater yam, during that period only required drip irrigation at 100% CPE (Nedunchezhiyan *et al.*, 2020). Among fertigation, the treatment F_3 resulted in significantly higher tuber yield (Fig. 2). The treatment F_3 recorded 20.5 and 6.6 % higher tuber yield that F1 and F_2, respectively. This showed that greater yam being a long duration and high yield potential crop requires higher nutrients. The lowest yield was found with the treatment F_1 (Fig. 2). The interaction between

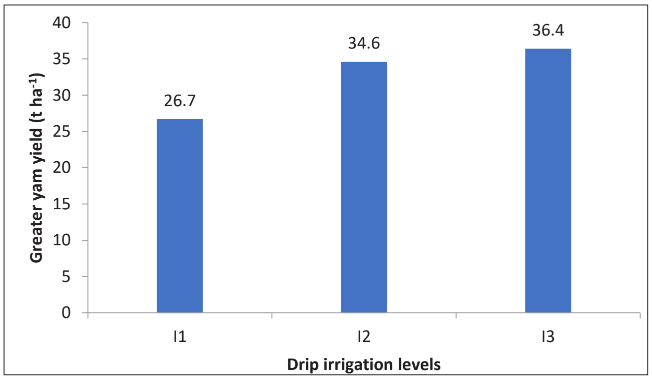


Fig. 1. Effect of drip irrigation levels on tuber yield (CD 0.05=2.0)

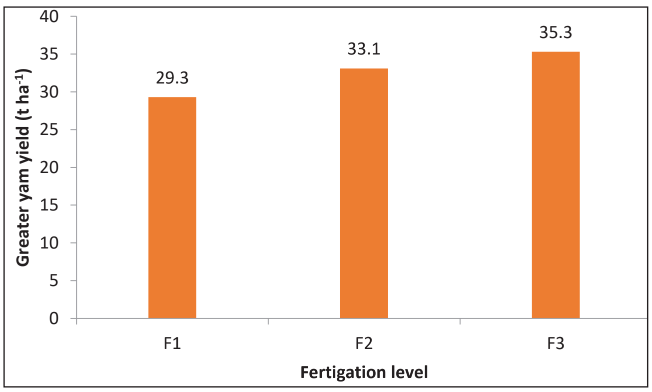


Fig. 2. Effect of fertigation levels on tuber yield (CD 0.05=0.9)

Table 1: Tuber yield, water- and fertilize-use efficiency as influenced by drip irrigation and fertigation levels

Treatment	Tuber yield (t ha-1)	Water-use efficiency (kg ha-mm-1)	Fertilizer-use efficiency (kg kg-1)
I1F1	22.9	35.2	127
I1F2	27.0	41.5	150
I1F3	30.1	46.3	167
I2F1	31.0	45.8	141
I2F2	35.3	52.1	160
I2F3	37.6	55.5	171
I3F1	33.9	48.2	131
I3F2	37.0	52.6	142
I3F3	38.1	54.1	146
C (NPK)	25.7	36.5	117
C	14.0	19.8	-
CD (0.05)	2.6	3.3	11

Table 2: Consumptive use/water requirement of greater yam

Consumptive use/ water requirement	Drip irrigation			Surface/ flood irrigation 100% CPE
	I1: 60% CPE	I2: 80% CPE	I3: 100% CPE	
Irrigation water (mm)	66.8	89.1	111.2	111.2
Effective rainfall (mm)	547.3	547.3	547.3	547.3
Soil profile contribution (mm)	15.4	14.2	12.6	14.8
Total (mm)	629.5	650.6	671.1	673.3

Table 3. Economics of greater yam cultivation as influenced by drip irrigation and fertigation levels

Treatment	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B:C ratio
Drip irrigation levels				
I1	186100	399900	213800	2.14
I2	194800	519800	325000	2.67
I3	197300	545700	348400	2.76
CD (0.05)	2700	30200	27600	0.12
Fertigation levels				
F1	186800	439200	252400	2.34
F2	193200	496800	303500	2.56
F3	198200	529400	331200	2.64
CD (0.05)	1300	14000	12800	0.06
Interaction				
I1F1	179800	343100	163300	1.91
I1F2	186400	405200	218800	2.17
I1F3	192000	451400	259400	2.35
I2F1	188500	465400	276800	2.47
I2F2	195000	529400	334400	2.72
I2F3	200800	564600	363700	2.81
I3F1	192000	509200	317200	2.65
I3F2	198300	555700	357400	2.80
I3F3	201700	572200	370500	2.83
C (NPK)	171300	385100	213800	2.25
C	135100	209300	74200	1.55
CD (0.05)	3200	38700	35700	0.17

irrigation and fertigation levels was found significant (Table 1). The treatment I_3F_3 resulted in higher tuber yield and it was statistically on par with I_2F_3 and I_3F_2 (Table 1). The treatments I_3F_3, I_2F_3 and I_3F_2 resulted in 48.2, 31.6 and 30.5% higher tuber yield than check (Table 1). These treatments further indicated that if equal quantity of fertilizers and water applied through soil with surface irrigation (check) and drip irrigation (I_3F_2), drip fertigation increased 30.5% tuber yield. This also indicated that drip fertigation increased water and fertilizer use efficiency. Nedunchezhiyan (2017) also reported similar information in elephant foot yam.

The treatment I_2F_3 resulted in higher water use efficiency (WUE) and it was followed by I_3F_3 and I_3F_2 (Table 1). The lower WUE was recorded drip irrigation at 60% CPE (I_1) in combination with any levels of fertilizer (I_1F_1, I_1F_2 and I_1F_3). Lower level of fertilizer application in higher level of drip irrigation at 80 and 100% CPE also recorded lower WUE (I_2F_1 and I_3F_1) (Table 1). The check registered higher WUE than control (Table 1). This indicated that WUE can also be increase by fertilizer application. The treatment I_2F_3 resulted in higher fertilizer use efficiency (FUE) (Table 1). The higher level of drip irrigation (I_3) with any quantity of fertilizer resulted in lower FUE (I_3F_1, I_3F_2 and I_3F_3) (Table 1). The lower fertilizer levels with any level of drip irrigation resulted in lower FUE (I_1F_1, I_1F_2, I_2F_1, I_2F_2, I_3F_1 and I_3F_2) (Table 1). Nedunchezhiyan *et al.* (2018) also observed similar result in elephant foot yam.

Eastern India receives high rainfall (1200 mm) during South-West monsoon. Long duration crops are planted/sown before monsoon with protective irrigation. In case of greater yam cultivation pre-monsoon irrigation is given for uniform sprouting and growth, whereas post-monsoon irrigation is given for rapid tuber bulking. In the present investigation higher amount of irrigation water was applied (pre and post monsoon) to the treatment I_3 followed by I_2 (Table 2). The consumptive use of water was ranged from 629.5-673.3 mm (Table 2). Effective rain fall is major contributor of consumptive use of water by the greater yam crop (Table 2). The irrigation water required during pre and post monsoon period was 66.8-111.2 mm (Table 2). Among drip irrigation, the consumptive use of water in the treatment I_3 was higher followed by I_2 (Table 2). Nedunchezhiyan *et al.* (2024) reported that about 900 mm was found optimum for greater yam+maize intercropping system.

Marked variation in cost of cultivation, gross return, net return and benefit:cost (B:C) ratio was noticed due to drip irrigation and fertigation levels (Table 3). The treatment I_3 resulted in higher cost of cultivation, gross return, net return and B:C ratio (Table 3). However, it was statistically on par with I_2. This was due to higher tuber yield in these treatments (Fig. 1). Among fertigation, the treatment F_3 resulted in significantly higher cost of cultivation, gross return, net return and B:C ratio (Table 3). This was due to higher tuber yield in this treatment (Fig. 2). The interaction between irrigation and fertigation levels was found significant (Table 3). The treatment I_3F_3 resulted in higher cost of cultivation and it was statistically on par with I_2F_3 (Table 3). This was due to higher tuber yield in this treatment (Table 1). The treatment I_3F_3 resulted in higher gross and net returns as well as B:C ratio and it was statistically on par with I_2F_3 and I_3F_2 (Table 3). Nedunchezhiyan *et al.* (2023b) also reported similar report in greater yam+maize intercropping system.

CONCLUSION

In greater yam, drip irrigation at 100%CPE along with fertigation of N- P_2O_5-K_2O 100-60-100 kg ha^{-1} (I_3F_3) and drip irrigation at 80%CPE along with fertigation of N- P_2O_5-K_2O 100-60-100 kg ha^{-1} (I_2F_3) were comparable in terms of tuber yield and returns. However, the treatment drip irrigation at 80%CPE along with fertigation of N- P_2O_5-K_2O 100-60-100 kg ha^{-1} (I_2F_3) saved 221000 litres (22.1 mm) of water per ha with higher WUE and FUE. Hence, in greater yam drip irrigation at 80% CPE along with fertigation of N- P_2O_5-K_2O 100-60-100 kg ha^{-1} (I_2F_3) can be recommended for optimum tuber yield, higher WUE and FUE and better returns.

ACKNOWLEDGEMENT

The authors are thankful to the Director, ICAR-Central Tuber Crops Research Institute, Thiruvananthapuram, for providing the facilities and supporting the work.

REFERENCES

Adomeniene A and Venskutonis P R. 2022. *Dioscorea* spp.: comprehensive review of antioxidant properties and their relation to phytochemicals and health benefits. *Molecules* **27**(8):2530.

Behera M S, Verma O P, Mahapatra P K, Singandhupe R B and Kumar A. 2013. Effect of irrigation and fertility levels on yield, quality and economics of Japanese mint (*Mentha arvensis*) under drip irrigation system. *Indian Journal of Agronomy* **58**(1): 109-13.

Chawla J K and Narda N K. 2002. Growth parameters of trickle fertigated potato. *Indian Journal of Agricultural Sciences* **70**(11): 747-52.

Ertek A, Sensoy S, Geddik I and Kuciikyumuk C. 2007. Irrigation scheduling for green capsicum (*Capsicum annum* L.) grown by field condition by using class A pan evaporation value. *American-Eurasian Journal of*

Agricultural and Environmental Science **2**(4): 349-58.

Manjunath M V, Shukla K N, Chauhan, H S, Singh P K and Singh R. 2001. Response of micro irrigation on various vegetables. *In*: *Proceedings of International Conference on Micro and Sprinkler Irrigation Systems*, 8-10 February 2000, Jalgoan Maharashtra, India, p 84.

Nedunchezhiyan M. 2017. Drip irrigation and fertigation effects on corm yield, water and fertilizer use efficiency and economics in elephant foot yam (*Amorphophallus paeoniifolius*). *Indian Journal of Agronomy* **62**(4): 519-24.

Nedunchezhiyan M and Sahoo B. 2019. Root and Tuber Crops. Kalyani Publishers, Ludhiana, India.

Nedunchezhiyan M, Byju G, Ravi V and James George. 2017. Spacio-temporal fertigation effects on growth, yield and nutrient use efficiency of elephant foot yam (*Amorphophallus paeoniifolius*). *American-Eurasian Journal of Agriculture & Environmental Science* **17**(1): 63-77.

Nedunchezhiyan M, Byju G, Ravi V and James George. 2018. Effect of fertigation schedule on production potential, quality and nutrient uptake of elephant-foot yam (*Amorphophallus paeoniifolius*). *Current Horticulture* **6**(1): 19-26.

Nedunchezhiyan M, Kalidas Pati, Chauhan, V B S and Arutselvan R. 2023b. Analysis of benefit: cost ratio in drip irrigation and fertigation in greater yam *(Dioscorea alata)* + maize *(Zea mays)* intercropping system. *Current Horticulture* **11**(1): 57-60. https://doi.org/10.5958/2455-7560.2023.00013.4

Nedunchezhiyan M, Kalidas Pati, Chauhan V B S and Jata S K. 2021. Enhancing factor productivity of a greater yam+maize intercropping system under drip fertigation. *Journal of Root Crops* **47**(1&2): 9-15.

Nedunchezhiyan M, Pati K, Chauhan V B S, Gowda K H, Arutselvan R., Laxminarayana K and Jata S K. (2024). Drip fertigation in greater yam+maize inter cropping system. *TF-5/2024/TSP* pp-1-4.

Nedunchezhiyan M, Pati K, Chauhan V B S, Arutselvan R, Laxminarayana, K, Byju G and Veena S S. 2020. Growth, dry matter production and yield characteristics of greater yam+maize intercropping system under varied drip irrigation and fertigation levels. *Journal of Root Crops* **46**(2): 14-22.

Nedunchezhiyan M, Sheela Immanuel, Jeeva ML, Kesava Kumar H, Visalakshi Chandra C and Chintha Pradeepika. 2023a. Yams, Technical Bulletin No.101, ICAR-Central Tuber Crops Research Institute, Sreekariyam, Thiruvananthapuram, Kerala, India, 32 p.

Nedunchezhiyan M, Suja G and Ravi V. 2022. Tropical root and tuber crops based cropping systems-a review. *Current Horticulture* **10**(1): 14-22. http://doi.org/10.5958/2455-7560.2022.00003.6

Panse V G and Sukhatme P V.1967. *Statistical Methods for Agricultural Workers*. ICAR, New Delhi, India.

Patel N and Rajput T B S. 2000. Effect of fertigation on growth and yield of onion. In: *Proceedings of International Conference on Micro and Sprinkler Irrigation system,* 8-10 February 2000, Jalgaon, Maharashtra, pp. 77.

Sinnadorai N, Kumar M, Bidyalakshmi D M, Jayashri Y J, Sweta M and Sanjeet K. 2022. Food, medicinal and ecological significance of Dioscorea bulbifera (Dioscoreaceae). In: Manjula BL, et al., editors. Yam. India, APRF p. 29-40

Sivanappan R K. 2004. Irrigation and rain water management for improving water use efficiency and production cotton crop. In: *Proceedings of International Symposium on Strategies for Sustainable Crop Production – A Global Vision*, November 23-25, UAS, Dharwad.

Tiwari K N, Singh A and Mal P K. 2003. Effect of drip irrigation on yield of cabbage (*Brassica oleracea* L var. *capitata*) under mulch and non-mulch conditions. *Agricultural Water Management* **58**: 19-28.

Vashi J M, Saravaiya S N, Desai K D, Patel A I, Patel H B and Sravani V. 2018. Effect of planting distance on growth and tuber yield of greater yam (*Dioscorea alata* L.) Under different growing conditions. *International Journal of Chemical Studies* **6**(4): 1475-81.

Current Horticulture **14(2): 84-88, April–June 2026**
DOI: 10.5958/2455-7560.2026.00024.6
Received: 2 April 2026; Accepted: 17 June 2026

Optimizing NPKS dosages for better morphological and yield traits of onion (*Allium cepa*) in *rabi* season in Jharkhand

Gourab Saha, Ananya Maji, Raj Kumar, Loino K Chishi, Shilpa Singha, Shantesh R Kamath, Krishna Prakash and Saheb Pal*

ICAR- Indian Agricultural Research Institute, Gauria Karma, Hazaribagh, Jharkhand, 825405, India

ABSTRACT

The experiment was conducted to evaluate the impact of varying NPKS dosages on morphological characteristics, quality and yield of onion (*Allium cepa* L.) cv. Pusa Madhavi during *rabi* season of 2024-2025 under agroclimatic conditions of Hazaribagh, Jharkhand. Randomized block design with nine treatments with variable dosages of NPKS, replicated six times was used. Analysis of variance revealed significant differences across treatment combinations. Application of N:P:K:S @ 140:112:112:56 kg/ha (T_5) recorded the maximum number of leaves and plant height \60 days after transplanting, number of scales/ bulb, total soluble solids and neck thickness of the bulbs at harvesting. The treatment also produced the maximum weight for ten bulbs which was found statistically at par with application of N:P:K:S @ 130:104:104:52 kg/ha (T_4). Moreover, highest total yield/ plot was recorded in T_4, followed by T_5, while the lowest yield was observed in T_9. The increasing levels of NPKS dosages promotes vegetative growth and bulb weight. However, T_4 resulted in the highest yield/ plot with a comparatively lower fertilizer dosage than T_5, making it potentially superior for maximizing growth and productivity of onion in Jharkhand.

Key words: Chotanagpur Plateau, Morphology, Nutrient Management, Quality, Yield.

Onion (*Allium cepa* L.) is one of the most important bulb crops cultivated in India. It belongs to the family Alliaceae, with a somatic chromosome number of 2n=2x=16 (Bal and Pal, 2020; Pal *et al.,* 2026). In India, Maharashtra, Gujarat, Karnataka, Andhra Pradesh, Tamil Nadu, Punjab, Haryana, Rajasthan, Uttar Pradesh, Bihar and West Bengal are the main onion-producing states (Tripathi *et al.,* 2017). It is cultivated in four different seasons, early-*kharif, kharif,* late-*kharif* and *rabi*. *Rabi* season onion is main crop as it can be stored for a longer period with proper storage facilities and has comparatively more area under cultivation. In India, it is grown in 1.54 million ha area with a production of 24.267 million tonnes and average productivity of productivity 15.76 tonnes/ha. While, in Jharkhand, it covers an area of 18.56 thousand ha with a production of 307.25 thousand tons, resulting in an average productivity of 16.55 tonnes/ ha (MA&FW, 2024). Thus, it is evident that though onion is grown in a relatively less area, its productivity in Jharkhand marginally supersedes that of national productivity, predominantly due to adoption of *kharif* onion in some districts, leading to better yield realization per unit area. However, small and marginal farmers grow *rabi* onion without application of recommended dosage of fertilizers, leading to poor productivity and quality. Other factors contributing to the low production are undulating topography, stony soil profile, poor water-holding capacity, lack of irrigation facility. A good agricultural practice, along with proper nutrient management, can boost the productivity as well as area expansion of *rabi* onion in Jharkhand as well as in the other parts of the Chotanagpur plateau region. Application of recommended dosage of fertilizers also results into thinner neck, reduces sprouting and thereby increases storage life of bulbs. Although, a common dose of NPKS of 100:80:80:40 kg/ha exists for *rabi* onion (Thamburaj and Singh, 2014), however, the recommended dosage varies across soil types and its inherent fertility status. Keeping these facts in mind, the experiment was conducted to standardize the recommended fertilizer dosage for *rabi* onion.

***Corresponding author :** saheb.horti@gmail.com

MATERIALS AND METHODS

The field experiment was conducted at ICAR-Indian Agricultural Research Institute, Hazaribagh, Jharkhand, during *rabi* season of 2024-2025. The experimental site is located in the Chotanagpur Plateau region at 24.2851°N latitude, 85.3600°E longitude at approximately 387.51 meters above mean sea level. The soil of experimental plot had a pH of 5.27 and EC of 0.035 ds/m. The available NPK of experimental plot was approximately 124.38, 14.48 and 120.50 kg/ ha, respectively. The experiment was laid down in a randomized block design with nine treatments (with variable dosage of N:P:K:S, replicated six times with each plot size of 1.0 m ×1.5 m. The details of treatment combinations evaluated have been presented in Table 1. The calculated dosage of nitrogen, phosphorus, potassium and sulphur was applied in the form of urea, single super phosphate, muriate of potash and wettable

Table 1: Variable dosage of NPKS evaluated

Treatment	N:P:K:S dosage (kg/ ha)				N:P:K:S dosage (g/ 1.5 m2)				Urea, SSP, MOP and wettable sulphur (80%WP) (g/ 1.5 m2)			
	N	P	K	S	N	P	K	S	Urea	SSP	MOP	Sulphur
T_1	100	80	80	40	15.00	12.00	12.00	6.00	33.00	75.00	19.20	7.50
T_2	110	88	88	44	16.50	13.20	13.20	6.60	36.30	82.50	21.12	8.25
T_3	120	96	96	48	18.00	14.40	14.40	7.20	39.60	90.00	23.04	9.00
T_4	130	104	104	52	19.50	15.60	15.60	7.80	42.90	97.50	24.96	9.75
T_5	140	112	112	56	21.00	16.80	16.80	8.40	46.20	105.00	26.88	10.50
T_6	90	72	72	36	13.50	10.80	10.80	5.40	29.70	67.50	17.28	6.75
T_7	80	64	64	32	12.00	9.60	9.60	4.80	26.40	60.00	15.36	6.00
T_8	70	56	56	28	10.50	8.40	8.40	4.20	23.10	52.50	13.44	5.25
T_9	60	48	48	24	9.00	7.20	7.20	3.60	19.80	45.00	11.52	4.50

sulphur (80%WP). Onion, variety Pusa Madhavi was used. The 45 days old seedlings were transplanted to main plots by maintaining a spacing of 15 cm between rows and 10 cm between plants, accommodating 100 plants in each plot. The half amount urea along with the entire quantity of SSP, MOP and elemental Sulphur was applied as the basal dose to each plot before transplanting. The remaining half amount of nitrogen was applied 26 days after transplanting. The plots were irrigated immediately after transplanting as well as when required to maintain sufficient moisture conditions to enable proper growth and development. Two hand weeding and hoeing were carried out, first at 25 days after transplanting and the other at 50 days after transplanting. After attaining more than 70% neck fall, bulbs were harvested. Recommended cultural practices were adopted for raising a healthy crop stand (Thamburaj and Singh 2014; Tripathi and Lawande 2019).

The plant height at 60 days after transplanting (DAT) was measured from the base of the plant to tip of the longest leaves using a measuring scale and number of leaves were counted simultaneously. At the time of harvesting, number of marketable bulbs were counted/ plot by discarding the undesired bulbs and yield/ plot was recorded. The bulbs were shifted to shade after six days of field curing following wind-row method. The neck thickness was measured using a digital vernier caliper 7 days after harvest. The bulbs were cut longitudinally into two halves and number of scales/ bulb were counted. The half-cut pieces were then crushed using a mortar and pestle to extract the juice for the estimation of total soluble solids and was expressed in °Brix, using a hand-held refractometer at room temperature. Ten bulbs were randomly selected from each plot for calculating average weight of ten bulbs. The data were analyzed using KAU Grapes Software Packages (Gopinath *et al.* 2021) at 5% level of significance.

RESULTS AND DISCUSSION

The analysis of variance depicted significant differences across the treatment combinations. The number of leaves/ plant at 60 days after transplanting (DAT) ranged from 10.667 in (T_9) to 12.302 (T_5) (Table 2). The performance of the other treatments, *viz.* T_1, T_2, T_3, T_6, T_7 and T_8 were found statistically similar to each other, while performance of T_5 was statistically superior to other treatments. The overall mean for this trait was recorded as 11.14. The number of leaves/ plant is a key determinant for yield of onion as it directly influences the photosynthesis. Generally, nitrogen promotes vegetative growth in plants. It was overserved that increasing levels of nitrogen increased the vegetative growth manifested in terms of number of leaves at 60 DAT. Previously, a similar increase in number of leaves/ plant was observed in onion by Vani *et al.* (2018) and Dhakad *et al.* (2019); Gour *et al.* (2023); Wabalepatil *et al.* (2023); Kumar *et al.* (2024) and Prakash *et al.* (2024).

Significant differences were also observed for plant height at 60 DAT in all treatment combinations. The mean plant height was 50.81 cm, with a maximum of 63.413 cm in T_5 and a minimum of 40.505 cm in T_9 (Table 2). The performance of T_9 was found statistically inferior among all other combinations, whereas T_5 was statistically superior over others. Thus, results indicated that variable application of macronutrients like NPKS significantly alters vegetative growth of onion plants. A consistent supply of a relatively higher quantity of nutrients promotes more plant height in onion. The plant height showed increasing trend with increase in application of the dosage of nitrogen, phosphorus, potassium and sulphur. Kumar *et al.* (2019) also found greater plant height in onion both at 45 and 90 DAT with application of 125 kg nitrogen and 50 kg each of phosphorus and potassium/ ha and by Gour *et al.* (2023) by application of 120:60:80:40 kg/ ha.

Significant differences were also observed for number of marketable bulbs/ plot. It was maximum in treatment T_6 (96.33 g), whereas treatment T_1 (control) was the lowest performing among all combinations (Table 2). The treatment combinations T_4, T_5, T_7, T_8 and T_9 were statistically at par with treatment T_6. The overall mean across the treatment combinations for this trait was recorded as 93.41 g. The coefficient of variation for this trait, *i.e.* 3.342% suggests good experimental precision with low variability among treatment combinations. The number of bulbs/ plot is another important determinant to maximize the return in onion production. Increase in marketable bulb yield was also observed by Dhakad *et al.* (2019) by applying 125:50:50 kg of chemical NPK fertilizers along with 20 tonnes of FYM/ ha over the other treatments comprising either similar or less dosage of NPK applied through organic inputs.

The highest neck thickness (14.892 mm) was observed in treatment T_5, which was statistically superior to lowest-performing treatment, T_9 (11.75 mm) (Table 2). The neck thickness in treatment T_4 (14.483 mm) was statistically at par with that of T_5, indicating no statistical difference between these treatments. The performance of T_3 showed intermediate neck thickness (13.557 mm), whereas T_1, T_2, T_6, T_7 and T_8 statistically inferior to highest performing treatment T_5. The performance of treatment T_9 was least in magnitude (11.795 mm) among all treatment combinations. The thickness of the neck at the time of harvest depends primarily on number of leaves/ plant and thickness of the leaves at harvest. A low to moderate neck thickness is generally desired as in minimizes moisture loss and prevents entry of pathogenic microorganisms, leading to longer post-harvest life. However, with increasing levels of nitrogen application, neck thickness increases correspondingly with increase in the leaf thickness and number of leaves/ plant. In our study, a similar trend was observed for this trait. The maximum neck thickness observed in T_5 seems primarily due to application of higher quantity of nitrogen over other treatments. These findings are in accordance with that of Dhakad *et al.* (2018), Kumar *et al.* (2024) and Swain *et al.* (2025).

The number of scales/ bulb ranged from 9.028 to 13.25, with an overall mean value of 10.67 (Table 3). The highest number of scales/ bulb was recorded in T_5, which was statistically superior over the other treatments. The treatment T_9 had the least number of scales/ bulb. It is evident from the data that, the number of scales/ bulb gradually increased with increase in fertilizer dosage from the RDF, while it decreased gradually with reduction in fertilizer dosage. Gour *et al.* (2023) recorded a similar trend. Kumar *et al.* (2024) recoded maximum number of scales/ bulb when onion crop was applied with 75% NPK of recommended dosage along with 25% FYM.

The total soluble solid content showed significant variations across treatment combinations with variable dosage of NPKS. The magnitude of TSS ranged from 9.778° Brix to 12.500° Brix, with an overall mean value of 11.24° Brix (Table 3). The treatment, T_5, showed maximum TSS value of 12.500° Brix, followed by 12.383° brix in T_4. A gradual decreasing trend of TSS was observed among treatment combinations T_3, T_2, T_1, T_6, T_7, T_8 and T_9 along with decrease in applied NPKS

Table 2: Effects of variable dosage of NPKS on plant morphological traits

Treatment	Traits observed#			
	No. of leaves at 60 DAT	Plant height (cm) at 60 DAT	No of marketable bulbs/ plot (g)	Neck thickness (mm)
T_1 (N:P:K:S @ 100:80:80:40 kg/ ha)	11.023c	48.733e	89.333c	12.907cd
T_2 (N:P:K:S @ 110:88:88:44 kg/ ha)	11.080c	51.448d	92.333bc	13.010cd
T_3 (N:P:K:S @ 120:96:96:48 kg/ ha)	11.123c	54.603c	91.667bc	13.557bc
T_4 (N:P:K:S @ 130:104:104:52 kg/ ha)	11.708b	57.548b	94.667ab	14.483ab
T_5 (N:P:K:S @ 140:112:112:56 kg/ ha)	12.302a	63.413a	93.500ab	14.892a
T_6 (N:P:K:S @ 90:72:72:36 kg/ ha)	10.855c	49.978de	96.333a	12.698cd
T_7 (N:P:K:S @ 80:64:64:32 kg/ ha)	10.843c	46.943f	94.500ab	12.833cd
T_8 (N:P:K:S @ 70:56:56:28 kg/ ha)	10.738c	44.090g	94.000ab	12.330cd
T_9 (N:P:K:S @ 60:48:48:24 kg/ ha)	10.667c	40.505h	93.833ab	11.795d
Overall Mean	11.14	50.81	93.41	13.16
S.E. (m) ±	0.172	0.608	1.274	0.449
C.D. (P≤0.05)	0.491	1.739	3.64	1.282
C.V. (%)	3.772	2.933	3.342	8.345

#Values followed by different letters indicate significant (p ≤ 0.05) differences

Table 3: Effect of variable dosage of NPKS on bulb yield and quality traits

Treatment	Traits observed#				
	No of scales per bulb	TSS (°Brix)	Weight of 10 bulbs (g)	Yield (kg/plot)	Yield (tonnes/ha)
T_1 (N:P:K:S @ 100:80:80:40 kg/ ha)	10.350e	11.233d	620.000d	4.207d	28.043d
T_2 (N:P:K:S @ 110:88:88:44 kg/ ha)	10.992d	11.617c	700.000c	4.580c	30.533c
T_3 (N:P:K:S @ 120:96:96:48 kg/ ha)	11.575c	11.967b	750.167b	4.787c	31.912c
T_4 (N:P:K:S @ 130:104:104:52 kg/ ha)	12.317b	12.383a	839.167a	5.598a	37.323a
T_5 (N:P:K:S @ 140:112:112:56 kg/ ha)	13.250a	12.500a	856.167a	5.212b	34.745b
T_6 (N:P:K:S @ 90:72:72:36 kg/ ha)	9.862f	11.058d	582.000e	3.762e	25.077e
T_7 (N:P:K:S @ 80:64:64:32 kg/ ha)	9.377g	10.475e	524.833f	3.488ef	23.255ef
T_8 (N:P:K:S @ 70:56:56:28 kg/ ha)	9.335g	10.177f	483.833g	3.300f	22.000f
T_9 (N:P:K:S @ 60:48:48:24 kg/ ha)	9.028g	9.778g	451.333h	2.627g	17.510g
Overall mean	10.67	11.24	645.27	4.17	27.822
S.E. (m) ±	0.152	0.064	8.277	0.102	0.678
C.D. (P≤0.05)	0.433	0.184	23.659	0.291	1.939
C.V. (%)	3.479	1.404	3.142	5.973	5.973

#Values followed by different letters indicate significant ($p \leq 0.05$) differences

dose. The TSS showed lowest coefficient of variation (%), suggesting a clear consistent effects of treatment combinations on the performance of this trait. The results of our study are in accordance with that of Brinjh *et al.* (2014), Behairy *et al.* (2015), Barman *et al.* (2023) and Getanesh *et al.* (2025).

The weight of ten bulbs ranged between 451.333 g to 856.167 g, with a mean value of 645.27 g (Table 3). The highest average bulb weight was recorded in treatment combination T_5. However, performance of T_4 was statistically at par with that of T_5. Further, these two treatment combinations (T_5 and T_4) were statistically superior to all the other treatments, indicating the influence of increasing fertilizer doses on dry matter accumulation in bulbs. The balanced supply of phosphorus and potassium helps in better energy transfer and cell expansion that ultimately led to better bulb size and bulb weight. Similarly, application of more quantity of NPKS in T_5 maximized weight of 10 random bulbs. The results are in line with that of Bhardwaj and Parashar (2024).

The highest yield/ plot (5.598 kg) was recorded with T_4 followed by T_5 (5.212 kg) (Table 3). However, lowest yield was recorded in treatment combination T_9 (2.627 kg), with an overall mean value of 4.17 kg, making them potential nutrient combinations for yield in *rabi* season where adoption of T_4 has been found to produce more yield over T_5 with comparatively lesser quantity of fertilizers. Similar performance was also observed for yield/ hectare. The results corroborate with that of Bhardwaj and Parashar (2023). The results of our study are also in accordance with that of Tesfay and Girmay (2019).

AUTHOR CONTRIBUTION

Dr. Saheb Pal conceptualized the experiment. Mr. Gourab Saha, Ms. Ananya Maji, Mr. Raj Kumar, Ms. Loino K. Chishi and Ms. Shilpa Singha conducted the experiment with assistance from Drs. Saheb Pal, Krishna Prakash and Shantesh R. Kamath. Dr. Saheb Pal wrote the manuscript. All authors have read and commented on the manuscript.

ACKNOWLEDGEMENTS

The authors are thankful the ICAR-Indian Agricultural Research Institute, Hazaribagh, Jharkhand, for providing all the necessary facilities for conducing this research.

DECLARATION

The authors declare that they do not have any conflict of interest.

REFERENCES

Bal, S. and Pal, S. 2021. Seed Production Technology of Onion. *In: Text Book on Vegetable Seed Production,* Mishra, N., Panigrahi, K.K. and Mani, A. (Eds). International Books & Periodical Supply Service, New Delhi, India, pp. 303-25.

Barman, G.D., Verma. S.K., Diwakar, S. and Parihar, S.S. 2023. Evaluate the organic and inorganic fertilizers doses for growth and yield of onion (*Allium cepa* L.) under Bilaspur Chhattisgarh region. *The Pharma Innovation Journal* **12**(7): 3174-76.

Behairy, A.G., Mahamoud, A.R., Shafeek, M.R., Ali, A.H. and Hafez, M.M.2015. Growth, yield and bulb quality of onion plants (*Allium cepa* L.) as affected by foliar and soil application of potassium. *Middle East Journal of Agriculture* **4**(1): 60-66.

Bhardwaj, R.L. and Parashar, A. 2023. Maximizing productivity in onion bulb cultivation through crop geometry and NPKS nutrient management. *Journal of Applied Horticulture* **25**(3): 308-12.

Bhardwaj, R.L. and Parashar, A. 2024. Crop geometry and nutrient (N-P-K-S) management for *kharif* onion bulb (*Allium cepa*) crop. *Indian Journal of Agricultural Sciences* **94**(8): 858-63.

Brinjh, S., Kumar, S., Kumar, M. and Kumar, M. 2014. Effects of integrated nutrient management on growth, yield and quality traits of onion cv. Pusa Madhavi. *Plant Archives* **14**(1): 557-59.

Dhakad, R.K., Chudasama, V.R., Verma, J., Jalpa, G. and Dhakad, M.K. 2019. Effect of INM in Onion (*Allium cepa* L.) with Respect to Growth and yield under North Gujarat Condition. *International Journal of Current Microbiology and Applied Sciences* **8**(4): 1618-22.

Getanesh, Y., Yeshiwas, T., Asnake, D. and Zelalem, S. 2025. Yield and quality performance of onion (*Allium cepa* L.) hybrid varieties in response to nitrogen fertilization in Northwest Ethiopia. BMC *Plant Biology* **26**: 101.

Gopinath, P.P., Prasad, R., Joseph, B. and Adarsh, V.S. 2021. grapesAgri1: Collection of Shiny Apps for Data Analysis in Agriculture. *Journal of Open-Source Software* **6**(63): 3437.

Gour, R., Roopesh, S. and Thakur, R.2023. Effect of integrated nutrient management on growth and yield of onion (*Allium cepa* L.) under Malwa Plateau of Madhya Pradesh. *International Journal of Statistics and Applied Mathematics* **SP-8**(5): 742-46.

Kumar, V., Rajvanshi, S.K. and Kumar, D. 2024. Study on Effect of INM on Growth, Yield and Quality of Onion (*Allium cepa* L.). *Environment and Ecology* **42**(4B): 1906-11.

MA&FW, New Delhi. 2024. Area and production of horticultural crops in India, Final Estimates 2023-2024. Ministry of Agriculture and Farmers' Welfare, Government of India.

Pal, S., Dedhia, L., Pavithra, K.N., Singh N., Prakash, K, Chauhan, V.B.S. 2026. Next-generation onion (*Allium cepa*) breeding using molecular markers: progress and prospects--a review. *Current Horticulture* **14**(1): 31-40.

Prakash, S., Singh, B., Kumar, M., Kumar, M., Singh, R., Kumar, A. and Kumar, M. 2024. Effect of INM and Natural Bio-stimulants for improving the growth, yield and bulb quality of onion (*Allium cepa* L.). *Plant Archives* **24** (2): 1452-56.

Swain. B., Kumar, S., Prajapati, N.K., Watke, A.G., Mohanty, S.P. 2025. Integrated nutrient approaches for maximizing growth, yield and quality in onion (*Allium cepa* L.) cv. Bhima Kiran. *International Journal of Advanced Biochemistry Research* **SP-9**(12): 965-69.

Tesfay, T. and Girmay, S. (2019). Economic Performance and Nutrient Use Efficiency of Onion (*Allium cepa* L.) Under N, K and S Nutrient Combinations in Northern Ethiopia. *The Open Agriculture Journal* **13**: 146-155.

Thamburaj, S. and Singh, N. 2014. *Textbook of Vegetables, Tuber crops and Spices*. Indian Council of Agricultural Research, New Delhi, 469p.

Tripathi, P.C. and Lawande K.E. 2019. Onion storage in tropical region- a review. **7**(2): 15-27.

Tripathi, P.C., Shankar, V. and Lawande, K.E. 2017. Microirrigation in onion (*Allium cepa*) and garlic (*A. sativum*) – a review. *Current Horticulture* **5**(1): 3-14.

Vani, F.B., Joshi, P.C., Verma, P., Sankhala, G.K. and Kumar, M. 2018. Effect of integrated nutrient management on yield of onion (*Allium cepa* L.) under North Gujarat condition. *International Journal of Chemical Studies* **7**(1): 2222-25.

Wabalepatil, R.S., Sonawane, D.A. and Sawle, D.D. 2023. Integrated nutrient management on growth and yield of *kharif* onion (*Allium cepa* L.). *International Journal of Chemical Research and Development* **5** (1): 18-24.

Current Horticulture **14**(2): 89-95, April–June 2026
DOI: 10.5958/2455-7560.2026.00025.2
Received: 5 May 2026; Accepted: 17 June 2026

Influence of transplanting dates on growth dynamics and harvest period of winter greenhouse cauliflower (*Brassica oleracea* var. *botrytis*) in Trans-Himalayan Ladakh, India

Kunzes Dolma, Tsering Stobdan, O. P. Chaurasia, Dattatray S. Dhavale and Vishal B. Mhetre*

DRDO- Defence Institute of High Altitude Research, Leh, Ladakh 901 205, India

Abstract

The study investigated the impact of various transplanting dates on growth, yield, and harvest period of cauliflower (*Brassica oleracea* var. *botrytis*) during the winter months within a passive solar Ladakh greenhouse in trans-Himalayan Ladakh region during 2023-24 at DRDO- Defence Institute of High Altitude Research, Leh, Ladakh. Two commercial cauliflower varieties, WS-909 and Amazing, were used with five distinct transplanting dates starting from 4 September 2023, to 14 October 2023 (2023-2024). Despite the extreme temperature fluctuations observed within the greenhouse, curd formation occurred in both varieties across all transplanting dates. The highest gross (1.15 and 0.98 kg), marketable (0.67 and 0.56 kg), and net (0.44 and 0.36 kg) curd weights for WS-909 and Amazing were recorded when transplanting took place on 4 September, 2023. A delay in planting date resulted in a corresponding decrease in gross, marketable, and net curd weights in both varieties. Additionally, increased temperatures in greenhouse contributed to a fuzziness range of 7.6% to 37.5% in harvested curds, which varied according to transplanting date and variety. The delays in transplanting were associated with reduced harvesting durations, decrease in total number of harvests, and, consequently, a decline in overall yield. It is thus suggested that cauliflower be transplanted early during first fortnight of September for optimal yield in this region. Nevertheless, late transplanting ensured availability of fresh cauliflower during peak winter months, and can be traded off with the reduced yield.

Key words: Cold arid region, Curd weight, Gross yield, High altitude, Ladakh greenhouse, Protected cultivation, Transplanting

Cultivating cauliflower (*Brassica oleracea* var. *botrytis*) in the trans-Himalayan Ladakh region demands innovative approaches to ensure food security and enhance income generation for local populace. Greenhouse cultivation, especially during winter, has become a promising solution to surmount these limitations (Angmo *et al*., 2020; Singh *et al*., 2024). Cauliflower is a cool-season crop that prefers moderate temperatures and uniform moisture regimes. It is cultivated for its immature inflorescence and is known as curd. Still, it happens to be a typical summer crop in Ladakh region, where transplanting is done in early-May and reaches maturity in July-September (Stobdan *et al*., 2018), and several environmental factors affect it at various growth stages (Hadley and Pearson, 1998). Thus, cauliflower cultivation is possible only through protected cultivation practices. Winter greenhouses, such as improvised passive solar greenhouses (Angmo *et al*., 2020; Krishna *et al*., 2025), designed to trap heat and maintain optimum growing conditions during cold season, enable farmers to grow cauliflower even when the outdoor temperature drops below freezing.

Transplanting time is an important factor affecting the growth and development of cauliflower. It influences the exposure of crop to environmental factors critical for growth, such as temperature, light intensity, and photoperiod; these, in turn, affect important physiological events, including germination, vegetative growth, curd formation, and maturation (Hafez *et al*., 2023; Chiranjiv *et al*., 2025). The optimal temperatures at different growth periods are very necessary for cauliflower. Excessively low temperatures or unseasonal warmth can lead to stunted growth, delay curd initiation, or produce low yields (Mulodia *et al*., 2022). Therefore, transplanting dates in high-altitude areas like Ladakh, with large variations in day lengths and large diurnal temperature fluctuations, must be appropriately synchronized with the existing conditions for optimal crop performance. Early transplanting exposes tender seedlings to low temperatures, which may delay growth and increase the chances of frost damage to the crop (Pradhan *et al*., 2023). Thus, study was carried out to evaluate the influence of different transplanting dates on growth dynamics, phenological development, harvest period, and yield of cauliflower in winter greenhouses.

MATERIALS AND METHODS

The experiment was conducted in a Ladakh passive solar greenhouse (Ladakh Greenhouse) at the Defence Institute of High Altitude Research in trans-Himalayan high-altitude region of Ladakh, India (altitude 3340 m from MSL, 34°08.2'N; 77°34.3'E) during 2023-24 winter

Corresponding author : vishal.mhetre@gov.in

season. The greenhouse is a medium-sized improvised passive solar greenhouse, measuring 90 feet in length, 27 feet in width, and 9 feet in height, oriented in an east-west direction. The structure features cement-plastered stone walls on three sides, with the east and west walls being 1.5 feet thick, while the north wall is 2 feet thick. The south-facing side is covered with a clear, UV-stabilized 16-mm triple-layer polycarbonate panel. A portion of the east and west walls is clad with a distinct material up to 4 feet. The greenhouse has a sloped wooden roof insulated on the northern side with a layer of straw and soil. Temperature regulation is achieved through manually operated ventilators located on the south-facing and west frames of the greenhouse. Notably, no supplementary lighting or heating systems were utilized, and the structure was not outfitted with a thermal blanket, even during the peak winter months. The temperature was recorded daily with a Hygro-Thermometer Clock (Extech Instruments, USA) (Table 1).

A randomized block design was implemented, with three replications per treatment. Each replication comprised plots measuring 2.1 m × 1.5 m, containing 20 seedlings arranged with a spacing of 35 cm × 35 cm. Farmyard manure (FYM) and vermicompost were applied during field preparation at 3.8 kg m^{-2} and 317 g m^{-2}, respectively. Throughout the growing season, no herbicides or pesticides were utilized. Irrigation was provided through flooding during the initial establishment phase and throughout subsequent growth stages at a weekly interval. Seedlings grown in a passive solar greenhouse were transplanted manually on five distinct dates: 4 September 2023, 14 September 2023, 24 September 2023, 4 October 2023, and 14 October 2023. Manual weeding was performed twice during the growing season to ensure optimal growth conditions.

Plant height, leaf count, and stem diameter were recorded 30-60 and 60-90 days after transplanting (DAT). Leaf chlorophyll index was assessed using the SPAD measurement method (Chlorophyll Meter SPAD-502Plus, Konica Minolta, Japan) on fully expanded upper leaves. Curd weight at fresh market maturity was measured three times throughout the season. All curds were trimmed to meet market standards before weighing. At harvest, plants were evaluated for curd quality defects, and curds exhibiting symptoms of physiological disorders were documented. Additionally, number of days taken for curd initiation, first harvest, peak harvest, and last harvest were calculated based on transplanting dates (DAT) for each planting date.

All experiments were conducted in triplicate to ensure reliability. The results of the experiments were presented as mean values ± standard deviation (SD). Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, SPSS Corporation, Chicago, Illinois, USA). A one-way analysis of variance (ANOVA) was executed, followed by post-hoc analysis employing a two-sided Tukey's Honestly Significant Difference (HSD) test, with a significance level set at $p \leq 0.05$.

RESULTS AND DISCUSSION

The data on plant height exhibited non-significant variation for WS-909 at 60 and 90 days after transplanting (DAT) (Table 2). In contrast, the Amazing variety displayed significant variation in plant height during the 60 DAT. The maximum plant height (49.4 cm) for the Amazing at 60 DAT was observed on 4 October 2023 DOT (date of transplanting), while minimum height (41.7 cm) was recorded on 14 September 2023 DOT. The variations in plant height across transplanting dates highlight the role of genetic and environmental factors in winter-grown greenhouse cauliflower growth. Over 90 DAT period, range of heights in Amazing variety narrowed, suggesting that while transplanting date influences early vegetative growth, genetic factors become more significant as plants mature and form curds. These findings align with Sultana *et al.* (2019).

The number of leaves/plant also did not vary significantly for variety WS-909; however, highest

Table 1: Temperature during cauliflower growing season in winter

Month	Temperature in open field (°C)		Temperature inside Ladakh Greenhouse (°C)		Difference in open field and greenhouse temperature (°C)	
	Max.	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**
September (2023)	23.1±3.3	9.3±3.3	49.3±4.4	15.5±2.0	25.2±2.5	5.8±1.0
October (2023)	13.3±3.1	-0.4±3.0	37.8±4.9	12.1±2.5	24.7±6.4	14.3±0.6
November (2023)	9.7±2.3	-5.0±3.1	37.3±2.4	6.5±1.0	28.4±2.6	13.2±0.7
December (2023)	4.6±1.4	-11.3±2.4	26.9±2.3	3.9±1.1	22.5±2.9	15.2±1.8
January (2024)	3.6±1.5	-12.2±2.0	23.5±2.3	1.5±1.2	20.4±2.9	13.0±2.5
February (2024)	0.5±3.0	-11.0±3.9	34.6±3.7	5.8±2.2	32.6±2.9	15.5±1.9
Mean	**9.1±8.2**	**-5.1±8.4**	**34.9±9.1**	**7.5±5.2**	**25.6±4.3**	**12.8±3.5**

Values represent mean±standard deviation (SD).

number of leaves was observed for 14 September 2023 DOT (20.1) at 90 DAT while lowest number of leaves was noted for 4 October 2023 DOT (18.0). For Amazing, at 60 and 90 DAT, highest number of leaves was noted for 4 September 2023 DOT (17.5; 21.3), whereas lowest number of leaves was recorded for 14 September 2023 (13.3). Similarly, Devi *et al.* (2022) reported that transplanting on November 23 resulted in a higher number of leaves/plant, attributing this to optimal environmental conditions that promote leaf development. Rahman *et al.* (2016) found that planting dates influenced leaf number, with specific dates providing conditions that enhance vegetative growth. These studies underscore the importance of selecting appropriate transplanting dates to optimize leaf development, which is crucial for photosynthetic capacity and overall plant vigour.

The analysis of stem diameter revealed non-significant variation in all transplanting dates for WSS-909 at 60 and 90 days after transplanting (DAT). This uniformity suggests that WS-909 maintains stable stem development regardless of transplanting time, indicating a potential resilience to varying environmental conditions within greenhouse setting. Notably, for Amazon variety, at 60 DAT, the largest stem diameter was observed on 4 September 2023 DOT, measuring 12.5 mm, whereas the smallest was recorded on 14 September 2023, at 9.1 mm. This pattern suggests that while early vegetative growth in Amazing variety may be influenced by transplanting date, stem development stabilizes as the plants mature.

However, a study by Hafez *et al.* (2023) reported that earlier transplanting dates increased stem diameter, attributing this to more favorable environmental conditions during the initial growth stages. Moreover, chlorophyll index values for both varieties, assessed across various transplanting dates, did not exhibit significant differences, ranging from 46.7±1.9 to 51.0 ± 1.9 at 60 and 90 days after transplanting (DAT). This consistency suggests that chlorophyll content in both varieties is relatively unaffected by the transplanting date, indicating a stable photosynthetic performance under greenhouse conditions. Similar observations were made by Akshatha *et al.* (2019), who found that different transplanting dates did not significantly impact chlorophyll content in broccoli, a close relative of cauliflower.

In our study, normal curds were successfully formed even though day temperatures exceeded 25 °C on most days (Fig. 1). This phenomenon may be attributed to the cumulative effects of lower temperatures on the plants, resulting in curd formation once the chilling requirement has been adequately fulfilled (Fujime and Hirose, 1980). No statistically significant variations in curd diameter (14.8 to 18.0 cm) were noted for Amazing and WS-909 varieties. This uniformity suggests that curd size in both varieties is relatively stable and less sensitive to timing of transplanting under the given conditions. In contrast, gross curd weight demonstrated an apparent decline with delayed transplanting.

Marketable and net curd weights followed this trend, with both varieties achieving peak weights on the earliest transplanting date and diminishing with subsequent delays (Table 3). The highest gross curd weight (1.15 kg; 0.98 kg), marketable curd weights (0.67 kg and 0.56 kg), and net curd weights (0.44 kg and 0.36 kg) of both varieties were recorded for 4 September 2023 DOT (date of transplanting), whereas lowest gross curd weight (0.79 kg) and marketable curd weight (0.44) in WS-909 were recorded for 14 October 2023 DOT. As the planting date was delayed, gross, marketable, and net curd weights for both varieties decreased correspondingly. A similar trend was observed for total marketable yield of both varieties. The total marketable

Table 2: Growth parameters of both varieties harvested in winter season (2023-2024)

Parameters	DAT*	WS-909					Amazing				
		Date of transplanting (DOT)					Date of transplanting (DOT)				
		4 Sep 23	14 Sep 23	24 Sep 23	4 Oct 23	14 Oct 23	4 Sep 23	14 Sep 23	24 Sep 23	4 Oct 23	14 Oct 23
Plant height (cm)	60	48.3±4.3^{a}	48.5±3.6^{a}	49.5±6.2^{a}	48.6±6.5^{a}	47.0±3.1^{a}	48.3±2.1^{ab}	41.7±1.3^{b}	47.0±5.6^{ab}	49.4±6.0^{a}	46.6±3.7^{ab}
	90	61.6±5.3^{a}	63.0±3.0^{a}	61.6±2.0^{a}	61.3±5.5^{a}	58.6±2.3^{a}	63.1±4.7^{a}	58.8±6.3^{a}	58.3±3.3^{a}	59.8±7.0^{a}	57.1±3.3^{a}
No. of leaves	60	16.1±2.1^{a}	15.1±1.6^{a}	15.1±1.3^{a}	14.6±0.8^{a}	14.8±0.9^{a}	17.5±2.0^{a}	13.3±0.8^{b}	15.5±1.2^{ab}	13.6±1.0^{b}	14.3±1.0^{b}
	90	19.6±1.0^{ab}	20.1±0.9^{a}	19.8±0.9^{ab}	18.0±1.2^{b}	19.1±1.4^{ab}	21.3±1.7^{a}	21.1±0.9^{a}	20.6±1.3^{a}	16.5±1.5^{b}	17.6±1.2^{b}
Stem diameter (mm)	60	12.5±1.6^{a}	12.4±1.6^{a}	13.1±0.4^{a}	12.3±1.4^{a}	11.9±1.1^{a}	12.5±1.1^{a}	9.1±0.3^{b}	11.6±2.2^{ab}	10.9±1.9^{ab}	10.6±1.2^{ab}
	90	16.4±1.7^{a}	18.0±1.5^{a}	17.0±1.0^{a}	15.7±1.6^{a}	15.9±1.4^{a}	16.6±1.6^{a}	14.3±1.1^{a}	14.3±1.2^{a}	14.3±2.6^{a}	14.9±1.3^{a}
Leaf chlorophyll (SPAD)	60	49.2±4.6^{a}	48.5±1.7^{a}	48.7±2.4^{a}	47.5±2.8^{a}	47.7±2.1^{a}	46.7±1.9^{a}	47.7±3.2^{a}	47.0±2.1^{a}	48.9±4.9^{a}	47.3±2.3^{a}
	90	49.5±3.4^{a}	48.9±2.2^{a}	49.6±2.7^{a}	49.0±2.9^{a}	51.0±1.9^{a}	48.1±2.3^{a}	50.0±2.0^{a}	47.6±1.9^{a}	49.2±3.1^{a}	49.3±1.6^{a}

Values represent mean±standard deviation (SD). Means followed by different lowercase letters within a row for each variety indicate significant differences (Tukey's HSD test, $p < 0.05$). *DAT- Days after transplanting

Fig. 1 Comparison between different transplanting dates at the time of first harvest of sequential dates of transplanting (DOT) for cauliflower seedlings

yield ranged from 2.1 to 3.5 kg m^{-2} and 1.6 to 2.1 kg/6.3 m^2 for WS-909 and Amazing, respectively.

Yield of both varieties declined with later transplanting dates, indicating that earlier planting confers a significant advantage in terms of total harvestable produce. Sultana *et al.* (2019) reported that planting cauliflower in November resulted in superior growth and yield, leading to highest economic and biological yields. Similarly, Devi *et al.* (2022) observed that cauliflower transplanted on 23 November achieved significantly higher yields than other dates, highlighting the importance of transplanting timing in maximizing productivity. The decrease in yield with delayed transplanting may be attributed to suboptimal environmental conditions encountered by plants during critical growth phases. Late transplanting can expose cauliflower to unfavorable temperature regimes and reduced light availability, adversely affecting photosynthetic efficiency and curd development. These environmental stresses contribute to reduced gross, marketable, and net curd weights observed in later transplanting dates.

However, marketable curd weight was significantly low compared to the yield potential of both varieties. The yield potential of WS-909 is 1.25-1.50 kg, and that of Amazing is 1-1.5 kg. Low curd weight may be due to higher temperatures inside greenhouse. High temperatures, specifically those exceeding 22.5-25 °C, are known to impact the diameter and weight of cauliflower curd negatively (Nowbuth, 1998; Gopalakrishnan, 2007). Additionally, Wheeler *et al.* (1995) documented reduced total biomass at the final harvest due to elevated temperatures. It has been observed that there is a decrease in dry weight of approximately 6% for every 1 °C increase in temperature. Delays in harvesting can lead to the formation of loose or yellow curds as a consequence of high temperatures. Gopalakrishnan (2007) indicated that curds developed in conditions exceeding 25 °C tend to appear small, loose, or yellow.

Physiological disorder

Several physiological disorders affect the market quality and yield of cauliflower curds. Fuzziness, characterized by a velvety or hairy appearance of curd, was noted in both varieties, with incidence rates ranging from 7.6 % to 13.6 % in WS-909 and from 15.5 % to 37.5% in Amazing, depending on the transplanting date (Table 3). Curd defects are associated with temperature fluctuations that fall outside the optimal range for a specific stage of development. Normal curds typically form within a temperature range of 10-25 °C, depending on variety. Fuzziness is observed when temperatures exceed this range, and its severity increases with rising temperatures (Fujime and Okuda, 1996). Also, fuzziness was more frequent with early transplanting dates, particularly in Amazing variety. Further, throughout the growing season, mean maximum temperature recorded in greenhouse was 34.9 °C, significantly above the ideal temperature range for curd development. Nevertheless, incidence of fuzziness observed among curds was relatively low. This phenomenon may be attributed to the severity of fuzziness, which tends to diminish when curds are subjected to elevated temperatures during later stages of development (Fujime and Okuda, 1996).

Harvest period

Different transplanting dates significantly impacted various attributes related to the harvest period (Table 4). The timing of curd initiation in cauliflower is a critical factor influencing yield and quality. The duration for curd initiation varied between 66.3 days and 81.3 days for WS-909 and Amazing varieties. Notably, seedlings transplanted on 4 September 2023 exhibited the longest duration for curd initiation in WS-909 variety, taking a total of 76 days, while minimum duration was recorded at 66.3 days for seedlings transplanted on 14 October 2023. Conversely, in Amazing variety, maximum days for curd initiation were noted for seedlings transplanted on 14 September 2023, which took 81.3 days, whereas minimum was recorded at 71.6±1.5 days for those transplanted on 4 September 2023. Wurr *et al*. (1990) demonstrated that the time from transplanting to maturity and from curd initiation to maturity in cauliflower is quadratically related to the transplanting date, with variations influenced by annual climatic differences.

The study found that later transplanting dates could either shorten or lengthen time to maturity, depending on year, due to temperature-mediated effects on vernalization and curd growth durations. Moreover, a study by Lin *et al*. (2019) found that tropical cauliflower cultivars exhibited different apex development rates under varying temperature treatments, with certain temperatures accelerating curd initiation. These findings underscore the importance of selecting appropriate transplanting dates to synchronize cauliflower development with favorable environmental conditions, thereby optimizing curd initiation timing.

The timing of transplanting significantly influenced the harvest dynamics of cauliflower varieties, as evidenced by the data on both varieties (Table 4). The seedlings transplanted on 14 October 2023 required longest period for first harvest in both varieties, which totaled 124 days. The peak harvest days for both varieties ranged from 114.6 days to 133.6 days, with peak harvest periods for all transplanting dates aligning closely. The interval for final harvest from transplanting date extended from 129.3 days to 151.6 days for all transplanting dates in both varieties. The total harvest duration from initial to final harvest varied between 5.3 days and 43.3 days for both varieties. The extended time to first harvest observed in the 14 October transplanting may be attributed to suboptimal environmental conditions encountered during critical growth phases. Later transplanting dates can expose cauliflower plants to cooler temperatures and reduced daylight, potentially delaying developmental processes such as curd initiation and maturation. Wurr *et al*. (1990) reported that time from transplanting to maturity in cauliflower is influenced by transplanting date, with later dates potentially leading to longer durations to maturity due to temperature-mediated effects on vernalization and curd growth. The variability in total harvest duration suggests that earlier transplanting dates may contribute to a more concentrated and potentially more manageable harvest period. This compression of harvest window can be advantageous for growers aiming to optimize labor and market timing. Conversely, later transplanting dates may result in a prolonged harvest period, which could complicate harvest logistics but also provide an extended supply of fresh produce to the market.

Table 3. Yield attributes of both varieties in winter season (2023-2024)

Variety	Date of transplanting	Curd diameter (cm)	Gross curd weight (kg)	Marketable curd weight (kg)	Net curd weight (kg)	Total marketable yield (kg)/m²	Fuzziness (%)
	4 Sep 2023	18.0±0.8[a]	1.15±0.0[a]	0.67±0.1[b]	0.44±0.0[a]	3.5±0.2[a]	12.0±0.4[bc]
	14 Sep 2023	17.0±1.3[a]	1.12±0.0[b]	0.57±0.0[ab]	0.38±0.0[a]	3.3±0.2[a]	7.6±0.4[d]
WS909	24 Sep 2023	17.1±1.1[a]	0.99±0.1[ab]	0.55±0.0[ab]	0.44±0.0[a]	2.9±0.3[b]	13.0±0.2[ab]
	4 Oct 2023	17.0±0.5[a]	0.86±0.0[b]	0.47±0.0[ab]	0.36±0.0[a]	2.2±0.1[c]	10.8±0.7[c]
	14 Oct 2023	16.6±0.2[a]	0.79±0.0[b]	0.44±0.0[b]	0.34±0.0[a]	2.1±0.2[c]	13.6±0.6[a]
	4 Sep 2023	15.5±0.5[a]	0.98±0.1[a]	0.56±0.0[a]	0.36±0.0[a]	2.0±0.2[a]	37.5±0.6[a]
	14 Sep 2023	15.0±0.8[a]	0.76±0.1[a]	0.44±0.1[a]	0.31±0.0[a]	1.6±0.2[b]	15.5±0.4[c]
Amazing	24 Sep 2023	15.3±0.5[a]	0.81±0.0[a]	0.48±0.0a	0.32±0.0[a]	2.0±0.1[a]	21.0±0.3[b]
	4 Oct 2023	14.8±1.0[a]	0.77±0.1[a]	0.45±0.0[a]	0.31±0.0[a]	2.1±0.2[a]	21.6±0.4[b]
	14 Oct 2023	14.8±1.0[a]	0.78±0.0[a]	0.46±0.0[a]	0.32±0.0[a]	1.9±0.3[a]	22.2±1.3[b]

Values represent mean±standard deviation (SD). Means followed by different lowercase letters within a row for each variety indicate significant differences (Tukey's HSD test, $p < 0.05$).

Table 4. Harvest period attributes of two commercial cauliflower varieties obtained in winter season (2023-2024)

Variety	WS909					Amazing				
Date of transplanting	**4 Sep 23**	**14 Sep 23**	**24 Sep 23**	**4 Oct 23**	**14 Oct 23**	**4 Sep 23**	**14 Sep 23**	**24 Sep 23**	**4 Oct 23**	**14 Oct 23**
Days for curd initiation (DAT)	76.0±1.0^{a}	72.6±1.5^{ab}	75.6±1.5^{ab}	71.3±2.5^{b}	66.3±1.5^{c}	71.6±1.5^{c}	81.3±1.5^{a}	72.3±2.0^{c}	76.3±1.5^{bc}	80.0±2.0^{ab}
Days to first harvest (DAT)	108.3±2.5^{b}	109.3±2.0^{b}	107.6±2.0^{b}	110.3±1.5^{b}	124.0±1.0^{a}	108.3±2.5^{b}	109.3±2.0^{b}	107.6±2.0^{b}	110.3±1.5^{b}	124.0±1.0^{a}
Date of peak harvest	29/12/2023	3/1/2024	23/1/2024	16/2/2024	16/2/2023	29/12/2023	3/1/2024	23/1/2024	7/2/2024	16/2/2023
Days to peak harvest (DAT)	114.6±1.5^{e}	129.3±2.0^{b}	119.6±0.5^{d}	133.6±1.5^{a}	124.0±1.0^{c}	114.6±1.5^{d}	129.3±2.0^{a}	119.6±0.5^{c}	124.6±1.5^{b}	124.0±1.0^{b}
Days to last harvest (DAT)	151.6±1.1^{a}	141.3±0.5^{b}	135.0±0.0^{c}	134.0±1.0^{c}	129.3±0.5^{d}	143.6±1.5^{a}	141.3±0.5^{a}	135.0±0.0^{b}	134.0±1.0^{b}	129.3±0.5^{c}
Harvest duration (days)	43.3±3.5^{a}	32.0±1.7^{b}	27.3±2.0^{bc}	23.6±1.5^{c}	5.3±1.5^{d}	35.3±0.5^{a}	32.0±1.7^{b}	24.0±1.0^{c}	23.6±0.5^{c}	5.3±1.5^{d}
No. of total harvests	6.0±1.0^{a}	4.0±0.0^{b}	3.6±0.5^{b}	2.6±0.5^{bc}	2.0±0.0^{c}	6.0±0.0^{a}	4.0±0.0^{b}	3.0±1.0^{bc}	2.6±0.5^{bc}	2.0±0.0^{c}
Interval between two successive harvests	7.5±0.1^{d}	9.2±0.2^{b}	8.3±0.2^{c}	11.0±0.2^{a}	4.0±0.1^{e}	7.5±0.1^{c}	9.2±0.2^{b}	10.9±0.1^{a}	11.0±0.2^{a}	4.0±0.1^{d}

Values represent mean±standard deviation (SD). Means followed by different lowercase letters within a row for each variety indicate significant differences (Tukey's HSD test, $p < 0.05$). *DAT- Days after transplanting

Specifically, seedlings transplanted on 4 September 2023 demonstrated the longest harvest duration, with WS-909 exhibiting 43.3±3.5 days and Amazing showing 35.3±0.5 days (Table 4). Additionally, number of harvests ranged from 2 to 6.0±1.0 for both varieties. Notably, maximum number of harvests for WS-909 (6.0±1.0) and Amazing (6.0±0.0) occurred with seedlings transplanted on 4 September 2023. Consequently, it is evident that delays in transplanting correlate with reduced harvest duration, a decrease in total number of harvests, and, as a result, a decline in overall yield. This suggests that optimal transplanting times are crucial for maximizing yield and extending the harvest period. As demonstrated in this study, early transplanting allows for extended harvest periods and increased harvest frequencies, thereby enhancing overall yield. These findings underscore the importance of aligning transplanting schedules with favorable environmental conditions to maximize cauliflower production.

CONCLUSION

Our findings demonstrate that transplanting dates significantly influence growth dynamics, yield attributes, and harvest duration. The transplanting on 4 September, 2023 resulted in highest curd weight, superior marketable yield, and an extended harvest period, while delays in transplanting led to a progressive decline in productivity and quality. Despite the substantial temperature fluctuations within the passive solar greenhouse, curd formation was achieved across all transplanting dates, confirming the feasibility of winter cauliflower production in this high-altitude environment. However, increased temperatures within the greenhouse also contributed to fuzziness in harvested curds, underscoring need for improved microclimate management strategies. Thus, it is recommended that transplanting of cauliflower should be done in early-September to maximize yield and marketable quality. Late transplanting of cauliflower may facilitate availability of fresh produce during the peak winter months; however, this practice may result in a reduced yield.

ACKNOWLEDGEMENTS

The study was supported by the Defence Research and Development Organization (DRDO), Ministry of Defence, Government of India.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Kunzes Dolma: Formal analysis; Investigation; Tsering Stobdan: Conceptualization; Methodology; Supervision; Writing – review and editing; O. P. Chaurasia: Project administration; Resources; Writing – review and editing; Dattatray S. Dhavale: Formal analysis; Investigation; Vishal B. Mhetre: Data curation; Validation; Visualization; Writing – original draft; Writing – review and editing

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.

REFERENCES

Akshatha N, Panchal B H and Mahida S. 2019. Study the effect of different dates of transplanting and spacing on yield and quality of broccoli (*Brassica oleracea* var. *italica*) cv. Palam Samriddhi in middle Gujarat condition. *International Journal of Chemical Studies* **7(4)**: 178–83.

Angmo P, Dolma T, Katiyar A K, Chaurasia O P and Stobdan T. 2020. Growing cauliflower in winter under passive solar greenhouse in Trans-Himalayan Ladakh, India. *Defence Life Science Journal* **5**: 192–97.

Chiranjiv, S M Haldhar, K I Singh, L N K Singh, Pranita Roy and S L Choudhary. 2025. Effect of transplanting dates on incidence of brinjal (*Solanum melongena*) shoot-and fruit-borer [*Leucinodes orbonalis* (Guenee)]. *Current Horticulture* **13(1)**: 75–79.

Devi P, Sharma A, Saini A and Sharma S. 2022. Effect of different spacing and transplanting dates on the growth and yield of cauliflower (*Brassica oleracea* var. *botrytis* L.). *International Journal of Advanced Research* **10(9)**: 280–88.

Fujime Y and Hirose T. 1980. Studies on thermal conditions of curd formation and development in cauliflower and broccoli. II. Effects of diurnal variation of temperature on curd formation. *Journal of the Japanese Society for Horticultural Science* **49**: 217–27.

Fujime Y and Okuda N. 1996. The physiology of flowering in Brassicas, especially about cauliflower and broccoli. *Acta Horticulturae* **407**: 247–54.

Giri H N, Sharma M D, Thapa R B, Pande K R, Khatri B B and Jha P K. 2023. Growth and yield of late season cauliflower (*Brassica oleracea* var. *botrytis* L.) varieties in Mid-Hill Region of Nepal. *Agricultural Science Digest* **43(1)**: 63–67.

Gopalakrishnan T R. 2007. Vegetable crops. In: Peter K V (Ed). *Horticulture Science Series Vol. 4*. New India Publishing Agency, New Delhi, India. pp. 199–224.

Hadley P and Pearson S. 1998. Effects of environmental factors on progress to crop maturity in selected Brassica crops. *Acta Horticulturae* **459**: 61–70.

Hafez H M, Ismail H E M A, Mohsen A A and Zyada H G. 2023. Effect of transplanting date on vegetative characters, leaf pigments and yield of some cauliflower hybrids under sandy soil conditions. *Zagazig Journal of Agricultural Research* **50(4)**: 437–50.

Krishna H, Singh S, Sharma S, Gowda M T, Kumar R, Panwar S, Pal G, Bahadur A, Tiwari S K, Srivastava K, Karuppaiah V, Singh A and Maheshwari S. 2025. Cost-effective and high-impact sustainable vegetable farming utilizing low tunnel technology: A review. *Current Horticulture* **13(1)**: 14-19.

Lin C Y, Chen K S, Chen H P, Lee H I and Hsieh C H. 2019. Curd initiation and transformation in tropical cauliflower cultivars under different temperature treatments. *HortScience* **54(8)**: 1351–56.

Mulodia V, Singh S K, Harith R C, Kumar Y and Kumar S N. 2022. Impact of high temperature stress on growth and yield of cauliflower. *Journal of Agrometeorology* **24(3)**: 290–94.

Nowbuth R D. 1998. The effect of temperature on curd initiation of cauliflower. In: Lalouette J A, Bachraz D Y, Sukurdeep N and Seebaluck B D (Eds). *Proceedings of the Second Annual Meeting of Agricultural Scientists*. Food and Agricultural Research Council, Rome, Italy. pp. 225–31.

Pradhan N G, Srivastava A, Shrestha A K and Gautam I P. 2023. Evaluation of cauliflower genotypes to different planting dates for early production in Kathmandu valley. *Nepal Agriculture Research Journal* **15(1)**: 82–97.

Rahman M A, Imran M, Ikrum M, Rahman M H and Rabbani M G. 2016. Effects of planting date and growth hormone on growth and yield of cauliflower. *Journal of Environmental Science and Natural Resources* **9(2)**: 143–50.

Singh B. 2024. Exploring potential of protected cultivation in India—a review. *Current Horticulture* **12(2)**: 3–11.

Stobdan T, Angmo S, Angchok D, Paljor E, Dawa T, Tsetan T and Chaurasia O P. 2018. Vegetable production scenario in Trans-Himalayan Leh Ladakh region, India. *Defence Life Science Journal* **3**: 85–92.

Sultana J, Mannan M A, Khan S A K U and Kamal M M. 2019. Planting date affects growth and yield performance of cauliflower (*Brassica oleracea* var. *botrytis*). *South Asian Journal of Agriculture* **7(1&2)**: 25–29.

Wheeler T R, Ellis R H, Hadley P and Morison J I L. 1995. Effects of CO2, temperature and their interaction on the growth, development and yield of cauliflower (Brassica oleracea L. botrytis). *Scientia Horticulturae* **60**: 181–97.

Wurr D C E, Fellows J R and Hiron R W P. 1990. Relationships between the times of transplanting, curd initiation and maturity in cauliflower. *The Journal of Agricultural Science* **114(2)**: 193–99.

Current Horticulture **14**(2): 96-99, April–June 2026
DOI: 10.5958/2455-7560.2026.00026.9
Received: 2 April 2026; Accepted: 17 June 2026

Effect of organic manure combinations on yield of chilli (*Capsicum annuum*) in Bundelkhand region

Safik Ahamad[1,2,5]*, J N Tiwari[2], Harpal Singh[2], R K Patel[3], Devideen Yadav[1], Abhilasha Pathak[4] and Pradeep Kumar[5]

[1]*ICAR-Indian Institute of Soil and Water Conservation, Dehra Dun, 24819, Uttrakhand, India*

Abstract

The experiment was conducted on chilli (*Capsicum annuum* L.) to evaluate the efficacy of eight distinct treatments: control (no manure), farmyard manure (FYM) 100% (20 t ha^{-1}), poultry manure (PM) 100% (2 t ha^{-1}), vermicompost (VM) 100% (3.33 t ha^{-1}), neem cake 100% (2 t ha^{-1}), FYM 50% (10 t ha^{-1}) + vermicompost 50% (1.66 t ha^{-1}), FYM 50% (10 t ha^{-1}) + PM 50% (1 ton ha^{-1}) and FYM 50% (10 t ha^{-1}) + neem cake 50% (1 t ha^{-1}), at the Karguwan Ji Institute of Agricultural Sciences, Bundelkhand University, during *rabi* season of 2019-2020. A randomized complete block design with three replications was employed. Applying 50% FYM (10 t ha^{-1}) + PM 50% (1 t ha^{-1}) significantly improved several plant characteristics. The results showed plant height of (56.70 cm), stem diameter (1.94 cm), 21 branches, 132 fruits/plant, fruit length of 8.63 cm, fruit diameter of 1.92 cm, average fruit weight of (1.59 g), fruit yield of (7.8 t $ha^{-1)}$, and 100g dry fruit weight 31.57g. Additionally, days to first flowering decreased to 40 days. Thus, this research offers valuable insights into optimizing organic manure usage to improve crop yield contributing farming systems overall sustainability and resilience.

Key words: Bundelkhand region, Growth, Organic manures, *Rabi* season, Yield

In arid region of Bundelkhand agriculture faces significant challenges due to persistent dry conditions, soil degradation and water scarcity (Garg *et al.,* 2020). These factors have made sustainable farming practices essencial for ensuring the viability and resilience of agricultural systems. Previous studies have consistently pointed to the need for more targeted approaches to combat the negative impacts of climate change on agriculture in arid regions, underscoring the importance of sustainable practices tailored to local environmental conditions (Baraj *et al.,* 2024; Sahoo *et al.,* 2024). Organic farming has gained traction globally, recognized for its numerous environmental benefits, including improved soil health, reduced chemical runoff and enhanced ecosystem services (Gamage *et al.,* 2023). However, despite its advantages, the adoption of organic practices in Bundelkhand, remains limited. This difficulty arises from the lack of region-specific research and a limited understanding of how various organic fertilizers can effectively improve crop yields under soil conditions of Bundelkhand (Kumar *et al.,* 2021). Thus, there has been a pressing need for region-specific research that focuses on optimizing organic inputs and addresses local farmers' concerns and challenges, such as water scarcity and soil degradation. Previous studies have demonstrated the positive effects of organic inputs on crop performance (Khaitov *et al.,* 2019).

There is a critical gap in understanding the most effective organic fertilizers for enhancing Chilli growth and yield in these arid agro-ecosystems. Still, comprehensive research focused on optimizing organic fertilizer combinations in this arid region is notably sparse (Verma *et al.*, 2020; Choudhary *et al.*, 2021). Research indicates that soil nutrient management is crucial for improving crop performance and the choice of organic inputs can significantly influence these outcomes (Rani *et al.*, 2023). However, specific needs of Bundelkhand's soil and climate remain underexplored. Therefore, evaluating the influence of various organic fertilizers on chilli yield seeks to enhance the resilience and its productivity in the region's unique agroclimatic conditions (Kumar *et al.*, 2022).

MATERIALS AND METHODS

The experiment was conducted during 2019–2020 *rabi* season at the Karguwan Ji at the Bundelkhand University Jhansi, Uttar Pradesh. Pusa Jwala variety was used in study with eight treatments organized in a randomized block design with three replications. These treatments included a control: no manure and various combinations and levels of organic manures such as 100% FYM (20 t ha^{-1}), 100% poultry manure (2 t ha^{-1}),

Corresponding author : safik.banda@gmail.com
[2] Institute of Agriculture Science, Bundelkhand University, Jhansi, Uttar Pradesh, India
[3] Regional Research Stations, Soil and Water Conservation, Datia, Madhya Pradesh
[4] Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttrakhand, India
[5] ICAR-Indian Grassland and Fodder Research Institute Jhansi, Uttar Pradesh, India

100% vermicompost (3.33 t ha^{-1}), 100% neem cake (2 t ha^{-1}), 50% FYM (10 t ha^{-1}) + 50% vermicompost (1.66 t ha^{-1}), 50% FYM (10 t ha^{-1}) + 50% poultry manure (1 t ha^{-1}) and 50% FYM (10 t ha^{-1}) + 50% neem cake (1 t ha^{-1}). In November 2019, chilli transplanting was carried out with a spacing of 60 × 45 cm. During the crop growth season activities such as hoeing, weeding and irrigation were conducted at appropriate intervals to support optimal crop growth and development. Different parameters, including plant height (cm), stem diameter (cm), number of branches plant, plant diameter (cm), number of fruits per plant, fruit length (cm), fruit diameter (cm), average fruit weight (g), dry fruit weight (g) (100g fresh weight then oven dry 105^0) and fruit yield (t ha^{-1}). The data on lant height (cm), stem diameter (cm), number of branches per plant, stem diameter (cm) were recorded 30 days after transplanting. Ripe fruits were carefully chosen from each plant, and the total weight of dried fruits was calculated in grams. The yield obtained from each experimental plot was converted and expressed as tonnes per hectare to standardize the results across treatment. The net plot size 2.70 x 2.20 m^2 and 16 plant per block.

The field was characterized by sandy loam soil with a neutral reaction (pH 7.1). Initial physico-chemical analysis revealed that the soil was low in available nitrogen (142 kg ha^{-1}) and phosphorus (4.5 kg ha^{-1}), while medium in available potassium (206 kg ha^{-1}). The organic carbon content was found to be 0.52%. Organic manure treatments were applied on a nutrient-equivalent basis ten days prior to transplanting to ensure precise delivery of the recommended nitrogen dose. The nitrogen content of manures used was: farmyard manure (0.50%), vermicompost (2.01%), poultry manure (2.70%), and neem cake (5.03%)." were applied ten days before transplanting at the time of final land preparation.

Statistical analysis:

The data were subjected to Analysis of Variance (ANOVA) using [Software Name, e.g., OPSTAT] as per the procedure for a Randomized Block Design. The significance of treatment effects was tested using the 'F' test at a 5% level of significance (p=0.05). Standard Error of Mean (SEm±) and Critical Difference (CD) were computed for comparing treatment means."

RESULTS AND DISCUSSION

The application of organic manures significantly influenced the growth parameters of plants (Table 1). Among the treatments, a combination of 50% farmyard manure (10 t ha^{-1}) and 50% poultry manure (1 t ha^{-1}) led to the most notable improvements in plant height, stem diameter, number of branches and days to first flowering compared to the control. The plants treated with 50% FYM + 50% poultry manure exhibited the maximum plant height (56.70 cm) and maximum stem diameter (1.94 cm), along with highest number of branches per plant (21.33) At 120 days after transplanting and earliest days to first flowering (39.66 days). These values were significantly better when compared to the control. The significant improvement in growth parameters with the integrated use of FYM and poultry manure is in close agreement with the findings of Verma *et al.* (2024), who reported that organic manures directly supply essential macro and micronutrients during mineralization. Similarly, Singh *et al.* (2011) observed that the microbial activity stimulated by organic matter produces humic acid and phytohormones, leading to early flowering and enhanced vegetative growth. Furthermore, Meena *et al.* (2023) also reported that the application of vermicompost and poultry manure creates a significant positive response on vegetative characters, plant height, and flowering attributes of solanaceous vegetable crops. Overall, treatments with poultry manure, vermicompost and neem cake also demonstrated considerable enhancements in growth parameters throughout the plant's life cycle. These findings are strongly supported by Yadav *et al.* (2024), who emphasized that application of diverse organic inputs optimizes the growth dynamics and vegetative parameters of vegetable crops. However, combination of FYM and poultry manure consistently outperformed other treatments in promoting robust growth and early flowering in chilli plants. Additionally, synergistic effects of these organic fertilizers likely created an ideal growth environment for chilli plants, leading to superior performance compared to other treatments.

The use of different organic manures had a significant impact on yield and fruit quality (Table 2). Among sole application of organic manures, use of 100% poultry manure resulted in highest number of fruits/plant (122.33), maximum fruit length (7.73 cm) and fruit diameter (1.60 cm), highest average fruit weight (1.46 g) and maximum dry fruit weight (26.95 g), consequently yielding the highest fruit yield (6.6 t ha^{-1}). The combination of 50% farmyard manure and 50% poultry manure exhibited maximum number of fruits/plant (132.33), maximum fruit length (8.63 cm) and fruit yield (7.8 t ha^{-1}) among all treatments. The superior performance of 100% poultry manure in sole application may be attributed to its balanced nutrient composition and higher organic matter content, promoting robust plant growth and fruit development.

Table 1: Effects of application of various combinations and levels of organic manures on growth parameters of chilli

Treatment	Plant height (cm)				Stem diameter (cm)				Number of branches per plant				Days taken to 1st flowering
Days after transplanting	30	60	90	120	30	60	90	120	30	60	90	120	
Control (no manure)	13.15	19.34	31.46	40.17	0.19	0.26	0.75	1.12	1.66	4.33	7.33	11.66	53.33
100% farm yard manure (FYM)	14.48	23.46	34.29	45.60	0.26	0.43	1.10	1.40	2.00	5.66	8.66	13.00	48.33
100% poultry manure	16.33	25.86	37.82	49.46	0.42	0.74	1.29	1.70	3.00	6.66	11.33	16.33	45.00
100% vermicompost	16.40	25.42	37.73	49.33	0.32	0.47	1.23	1.53	2.33	6.66	10.66	16.00	44.66
100% neem cake	16.23	24.20	36.39	46.48	0.29	0.43	1.19	1.42	2.00	6.00	9.33	14.00	47.66
50% FYM + 50% vermicompost	16.94	26.33	38.52	50.92	0.44	0.82	1.37	1.84	3.33	8.33	13.00	17.66	43.00
50% FYM + 50% poultry manure	18.70	28.36	40.49	56.70	0.49	0.90	1.56	1.94	4.00	9.66	14.66	21.33	39.66
50% FYM + 50% neem cake	15.51	24.59	36.68	47.78	0.35	0.62	1.22	1.65	2.00	6.33	11.33	16.00	46.66
SE (m) ±	0.35	0.66	0.54	0.22	0.008	0.009	0.009	0.011	0.28	0.38	0.27	0.49	0.43
C.D. (5 %)	1.08	2.04	1.67	0.69	0.024	0.013	0.013	0.034	0.87	1.16	0.83	1.52	1.33

Table 2: Effects of application of various combinations and levels of organic manure on yield attributes of chilli

Treatment	Number of fruits per plant	Fruit length (cm)	Fruit diameter (cm)	Average Fruit weight (g)	Dry fruit weight (g)	Fruit yield (t ha^{-1}) (calculated)
Control (no manure)	102.00	5.32	1.12	1.18	23.99	4.5
100% farm yard manure (FYM)	106.33	6.30	1.37	1.23	25.52	4.9
100% poultry manure	122.33	7.73	1.60	1.46	26.95	6.6
100% vermicompost	116.66	7.30	1.55	1.27	26.82	5.5
100% neem cake	113.00	6.43	1.39	1.26	25.84	5.3
50% FYM + 50% vermicompost	127.33	8.25	1.71	1.53	27.52	7.2
50% FYM + 50% poultry manure	132.33	8.63	1.92	1.59	31.57	7.8
50% FYM + 50% neem cake	120.66	7.05	1.43	1.32	26.04	5.9
SE (m) ±	0.85	0.087	0.041	0.011	0.32	0.07
C.D. at 5 %	2.62	0.26	0.12	0.035	0.99	0.21

These observations are in close conformity with Choudhary *et al.* (2021), who also recorded significant enhancement in yield attributes and overall fruit yield of chilli through strategic application of organic manures. The synergistic effects observed with the combination of farmyard manure and poultry manure suggest a complementary nutrient profile, enhancing both plant vigour and fruit yield, potentially due to combined benefits of different organic sources enriching soil fertility and promoting nutrient availability for optimal plant uptake. Furthermore, Sharma *et al.* (2023) confirmed that such organic combinations play a vital role in maintaining soil fertility and yield sustainability of vegetable crops over time.

CONCLUSION

Thus, combined application of 10 t ha^{-1} FYM and 1 t ha^{-1} poultry manure is highly recommended for chilli cultivation in the Bundelkhand region. This strategy not only maximizes fruit productivity (7.8 t ha^{-1}) but also offers a sustainable pathway to enhance soil health and resilience against region's harsh climatic conditions.

ACKNOWLEDGEMENTS

We sincerely acknowledge the help of Bundelkhand University for providing essential facilities and support to conduct this research.

Data Availability Statement

Data will be available on request

Conflict of interest

The authors declare that there is no conflict of interest.

Authors' contribution:

Safik Ahamad conducting research, data recording, and analysis, J. N. Tiwari-supervising and original hypothesis of research, Harpal Singh- writing, RK Patel- review and writing, Abhilasha Pathak , Pradeep kumar editing, Devideen Yadav- writing,

REFERENCES

Baraj, B., Mishra, M., Sudarsan, D., da Silva, R.M. and Santos, C.A.G. 2024. Climate change and resilience, adaptation, and sustainability of agriculture in India: A bibliometric review. *Heliyon* **10**(2): e25412.

Choudhary, M. R., Dhaka, R. S. and Jajoria, M. 2021. Response of chilli (*Capsicum annuum* L.) to organic manures and biofertilizers under semi-arid conditions. *Current Horticulture* **9**(1): 42–45.

Gamage, A., Gangahagedara, R., Gamage, J., Jayasinghe, N., Kodikara, N., Suraweera, P. and Merah, O. 2023. Role of organic farming for achieving sustainability in agriculture. *Farming System* **1**(1): 100005.

Garg, K.K., Singh, R., Anantha, K.H., Singh, A.K., Akuraju, V.R., Barron, J., Dev, I., Tewari, R.K., Wani, S.P., Dhyani, S.K. and Dixit, S. 2020. Building climate resilience in degraded agricultural landscapes through water management: A case study of Bundelkhand region, Central India. *Journal of Hydrology* **591**: 125592.

Khaitov, B., Yun, H. J., Lee, Y., Ruziev, F., Le, T. H., Umurzokov, M. and Park, K. W. 2019. Impact of organic manure on growth, nutrient content and yield of chilli (*Capsicum annuum* L.) under various temperature environments. *International Journal of Environmental Research and Public Health* **6**(17): 3031.

Kumar, D., Ranjan, R., Meena, M.K., Yadav, R.S., Gupta, G., Jinger, D., Yadav, D. and Pramanik, M. 2021. Exploring conservation agricultural practices in Bundelkhand region, Central India. In: *Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security*, Springer, pp.195-222.

Kumar, R., Meena, M. L. and Shukla, A. K. 2022. Productivity and quality enhancement of hot pepper (*Capsicum annuum*) through integrated organic nutrient management. *Current Horticulture* **10**(2): 28–32.

Meena, H. L., Singh, A. and Yadav, R. 2023. Effect of vermicompost and poultry manure on growth, flowering and yield attributes of solanaceous vegetable crops. *Current Horticulture* **11**(1): 18–22.

Rani, M., Kaushik, P., Bhayana, S. and Kapoor, S. 2023. Impact of organic farming on soil health and nutritional quality of crops. *Journal of the Saudi Society of Agricultural Sciences***22**(8): 560-569.

Sahoo, S., Singha, C., Govind, A. and Moghimi, A. 2024. Review of Climate-Resilient Agriculture for Ensuring Food Security: Sustainability Opportunities and Challenges of India. *Environmental and Sustainability Indicators* **21**: 100544.

Sharma, P. K., Devi, S. and Kumar, A. 2023. Soil fertility and yield sustainability of vegetable crops as influenced by different organic inputs. *Current Horticulture* **11**(3): 35–39.

Singh, G., Kumar, D. and Sharma, P. 2015. Effect of organics, biofertilizers and crop residue application on soil microbial activity in rice–wheat and rice-wheat mungbean cropping systems in the Indo-Gangetic plains. *Cogent Geoscience* **1**(1): 1085296.

Verma, R., Kumar, R., Maveril, K., Panzade, P.P., Kumar, A., Kumar, A. and Solanki, P. 2025. Influence of Organic Manures and Chemical Fertilizers on the Yield and Yield-Attributing Characteristics of Rice. *Journal of Experimental Agriculture International* **47**(12): 695-702.

Verma, S. K., Mishra, R. K. and Panday, A. K. 2020. Organic nutrient management for sustainable production of chilli in Central India. *Current Horticulture* **8**(2): 51–55.

Yadav, D., Singh, H. and Pathak, A. 2024. Evaluation of various organic manures for growth dynamics and yield optimization of vegetable crops. *Current Horticulture* **12**(1): 15–19.

Current Horticulture **14**(2): 100-106, April–June 2026
DOI: 10.5958/2455-7560.2026.00027.5
Received: 21 April 2026; Accepted: 17 June 2026

Effect of organic, integrated and conventional management on growth, yield and soil health in cassava (*Manihot esculenta*) - vegetable intercropping systems

Sarika Nandan and G Suja*

ICAR-Central Tuber Crops Research Institute, Sreekariyam, Thiruvananthapuram 695 017, Kerala, India

Abstract

The experiment was conducted to evaluate the effects of organic, chemical, and integrated management methods on growth, yield, dry-matter production, and soil physical and chemical parameters of cassava (*Manihot esculenta* Crantz) -vegetable intercropping at ICAR-Central Tuber Crops Research Institute (ICAR-CTCRI), Sreekariyam, Thiruvananthapuram, Kerala, India, during 2021. The split plot design consisted of three vegetables, amaranthus (*Amaranthus* spp.), okra [*Abelmoschus esculentus* (L.) Moench] and vegetable cowpea [*Vigna unguiculata* (L.) Walp] in main plots and four management options, 100% organic, 75% organic + innovative practices, integrated and package of practices (POP) in subplots. The 75% organic + innovative practices exhibited significantly higher harvest index and tuber dry matter production at 9 MAP, tuber yield, tuber dry matter% and mean tuber bulking rate. Highest tuber equivalent yield was observed in cassava-okra intercropping system under 75% organic + innovative practices. Soil organic C, available N and available Zn were significantly higher in 100% organic practices, and exchangeable Ca in 75% organic + innovative practices. Thus, organic management imparted significant effect on soil chemical properties, which was reflected in higher yields.

Key words: Cassava-Vegetable system, Intercropping, Organic farming, Tuber equivalent yield

Cassava (*Manihot esculenta* Crantz) is a drought-tolerant, staple food crop that is grown in tropical and subtropical areas that plays a vital role in global food security. High calorific value and environmental adaptability are the major factors that make cassava a staple food in areas affected by chronic food shortages, where conventional staples are insufficient (Bayata 2019). Cassava-based multi-cropping systems have long been practised by smallholder farmers in tropical regions across Africa and Asia to enhance agroecosystem resilience and household food security (Ravi *et al*., 2021; Nedunchezhiyan *et al*., 2022; Suja *et al.,* 2025). As the demand for organic vegetables has risen in recent years globally, the integration of short-duration vegetable crops like amaranthus (*Amaranthus* spp.), okra [*Abelmoschus esculentus* (L.) Moench] and cowpea [*Vigna unguiculata* (L.) Walp], as intercrops in organically managed cassava systems can offer nutritional enrichment and agroecological benefits.

The effect of organic management on crop productivity, produce quality and soil health in tropical tuber crops is well documented (Suja *et al*., 2012; Suja and Sreekumar, 2014; Suja *et al*., 2017; Seena Radhakrishnan *et al.,* 2022). Intercropping, however, involves complex plant-to-plant and plant-to-soil interactions that differ significantly from monocropping due to resource competition and complementarity in terms of light, water, and nutrients (Willey, 1979; Lithourgidis *et al*., 2011; Brooker *et al*., 2015). Despite the long-standing practice of cassava-based intercropping among smallholder farmers in tropical regions (Ravi *et al*., 2021; Nedunchezhiyan *et al*., 2022), there is limited systematic research evaluating the performance of short-duration vegetables under organically managed cassava systems.

Most comparative nutrient management studies have been conducted either in monocropped cassava or in cereal-legume systems (Velten *et al*., 2015; Ravisankar *et al.,* 2021), with limited emphasis on tropical tuber crop-vegetable intercropping systems. Addressing these research gaps is essential for developing scientifically validated technologies that enhance productivity, soil health, and nutritional diversification in sustainable cassava-based organic farming systems. The present study aims to develop technologies for organic production of short-duration vegetables like amaranthus, okra and cowpea in association with cassava and to evaluate the effect of organic, integrated and chemical management options on growth, yield and soil properties, in cassava + vegetable intercropping system.

MATERIALS AND METHODS

Field experiments were conducted during January-October in 2021 at ICAR-CTCRI (8° 29' N, 76°57'E, 52 m altitude), Thiruvananthapuram, Kerala, India. Chemical inputs were not used for six years before taking up the

Corresponding author : suja.g@icar.org.in

current research. The soil of experimental site was acidic in reaction (pH: 4.34), with low available N (132.71 kg/ha), and organic C (0.48), high available P (101.52 kg/ha) and high available K (334.95 kg/ha). The site experiences a typical humid tropical climate. During the experimental period, total rainfall received was 1544.61 mm, maximum and minimum temperatures were 31.79 and 24.77°C respectively, and mean relative humidity was 81.40%.

The experiment was laid out in a split plot design with cassava variety, Sree Reksha, intercropped with amaranthus (Arun), okra (Anjitha) and vegetable cowpea (bush type) (Anaswara) in main plots and four management options, 100% organic, 75% organic + innovative practices, integrated (50% organic +50% inorganic) and package of practices in sub plots (Table 1). The gross plot size was 5.4 m × 5.4 m, accommodating 16 net plants. Observations on total biomass production and partitioning to leaf, stem and tuber of cassava were made 3, 6 and 9 months after planting (MAP). Based on these, growth indices, viz. leaf area index (LAI), crop growth rate (CGR), relative growth rate (RGR), harvest index (HI), tuber bulking rate (TBR) and mean TBR of cassava were computed using growth analysis techniques of Hunt (1982). Fresh tuber yield of cassava and yield of vegetables were collected from the net plants and expressed in tonnes/ha. Tuber equivalent yield was calculated based on yields of component crops (Devasenapathy *et al.*, 2009).

Physical characters of soil such as bulk density, particle density, water-holding capacity and porosity

Table 1: Description of management options

Management	**Inputs and quantity**			
	Cassava	**Amaranthus**	**Okra**	**Vegetable cowpea**
100% organic	FYM @ 12.5 t/ha *in situ* green manuring @10 t/ha PGPR mix 1@ 250 kg/ha crop residue @ 3 t/ha	FYM @ 25 t/ha poultry manure @ 12 t/ha vermicompost @ 3.35 t/ha neem cake @ 1.675 t/ha ground nut cake@ 350 kg/ha and P_2O_5 @ 15 kg/ha as Mussoorie phosphate @ 75 kg/ha	FYM @ 12 t/ha poultry manure @ 4.2 t/ha vermicompost @ 3.35 t/ha neem cake @ 1.675 t/ha groundnut cake @ 350 kg/ha	FYM @ 10 t/ha poultry manure @ 4.2 t/ha vermicompost @ 660 kg/ha neem cake @ 660 kg/ha
75% organic + innovative practices	FYM @ 12.5 t/ha *in situ* green manuring @ 10 t/ha PGPR mix 1 @ 250 kg/ha *Panchagavya*, Vermiwash, Cow urine, *Jeevamrit*	FYM @ 18.75 t/ha poultry manure @ 9 t/ha vermicompost @ 2.5 t/ha neem cake @ 1.26 t/ha Groundnut cake @ 265 kg/ha P_2O_5 @ 11.25 kg/ha as Mussoorie phosphate @ 56.25 kg/ha *Panchagavya*, vermiwash, Cow urine, *Jeevamrit*	FYM @ 9 t/ha poultry manure @ 3.15 t/ha vermicompost @ 2.5 t/ha neem cake @ 1.26 t/ha groundnut cake @ 265 kg/ha *Panchagavya*, vermiwash, Cow urine, *Jeevamrit*	FYM @ 7.5 t/ha poultry manure @ 3.15 t/ha vermicompost @ 500 kg/ha Neem cake @ 500 kg/ha *Panchagavya*, vermiwash/ Cow urine, *Jeevamrit*
Integrated (50% Organic + 50% Inorganic)	FYM @ 12.5 t/ha PGPR mix 1 @ 250 kg/ha NPK @ 80:37.5:75 kg/ha	FYM @ 12.5 t/ha poultry manure @ 3.5 t/ha Vermicompost @ 1.675 t/ha neem cake @ 0.850 t/ha groundnut cake @ 175 kg /ha PGPR mix 1 @ 250 kg/ha NPK @ 175:75:125 kg /ha	FYM @ 15 t/ha poultry manure @ 0.850 t /ha PGPR mix 1 @ 250 kg/ha NPK @ 105:35:75 kg/ha	FYM @ 10 t/ha PGPR mix 1 @ 250 kg/ha NPK @ 60:35:45 kg/ha
Package of Practices (POP)	FYM @ 12.5 t/ha NPK @ 100:50:100 kg/ha	FYM @ 50 t/ha NPK @ 100:50:50 kg/ha	FYM @ 20 t/ha NPK @ 110:35:70 kg/ha	FYM @ 20 t/ha NPK @ 20:30:10 kg/ha

were estimated as per the methods of Gupta and Dakshinamoorthy (1980). The pH, organic C, available N, P, K, Ca, Mg, Fe, Zn and Cu status of soil were estimated by standard analytical methods (Page *et al.,* 1982). Data were analyzed by ANOVA for split-plot design with three replications, with intercropping systems in whole plots and management options in subplots. The main plot factor was tested against whole plot error and the subplot factor and interaction against subplot error. Treatment means were compared using the critical difference at 0.05 significance level, utilizing SAS statistical software (Version 9.3).

RESULTS AND DISCUSSION

During initial and mid growth phases, management options did not influence leaf biomass, but 100% organic plots tended to produce higher leaf biomass during both phases (60.62 and 314.87 g/plant respectively). At harvesting, organically raised plants produced higher leaf biomass (431.47 g/plant) on a par with conventional plants. Stem biomass production was not significantly influenced by the management options throughout the growth phases. However, organically grown plants produced numerically more stem biomass compared to conventional plants during first and final stages (10.96 and 315.50 g/plant respectively).

During initial stage, management options did not vary significantly in tuber biomass production, but 75% organic + innovative practices appeared to have higher tuber biomass (38.81 g/plant). Tuber biomass was significantly influenced by management options during second and third growth phases. In mid growth phase, 50% organic + 50% inorganic practice increased tuber biomass on a par with 75% organic + innovative practices and 100% organic practice (700.26, 657.32 and 610.29 g/plant respectively). At harvesting, 75% organic + innovative practices produced significantly highest tuber dry matter (955.82 g/plant). Significantly highest tuber dry matter percentage was observed in 75% organic + innovative practices (25.38%). There was no significant difference in total dry matter production among management options.

However, both 100% organic and 75% organic + innovative practices produced relatively more total plant biomass compared to conventional plants during initial and final growth phases. At harvesting, 75% organic + innovative practices showed comparatively higher values, followed by 100% organic resulted in higher total dry matter production (1570.15 and 1457.35 g/plant respectively). Thus organically managed plots showed a favourable trend in phasic course of biomass production and its partitioning to various plant parts. The greater contribution of major, secondary and micronutrients from the organic resources such as green manure cowpea, vermicompost, neem cake, groundnut cake and poultry manure in comparison to other practices might have contributed to the increased biomass accumulation under organic management. This confirms studies of Suja *et al.* (2012), Suja *et al.* (2017) and Seena Radhakrishnan *et al.* (2022).

Leaf Area Index (LAI) peaked at the mid growth phase and decreased slightly towards final phase. The management options did not significantly influence LAI, however 100% organic practice resulted in slightly higher LAI by first and final stages (1.76 and 2.96 respectively), while in mid stage, 50% organic + 50% inorganic practices resulted in relatively higher LAI values, followed by 100% organic practice (4.38 and 3.91 respectively). These findings are consistent with those of Almunqedhi *et al.* (2025). Seena Radhakrishnan *et al.* (2022) also observed similar results in cassava.

Both organically managed practices showed numerically higher Crop Growth Rate (CGR) values at the initial growth stage with 100% organic, resulting in marginally higher CGR followed by 75% organic + innovative practices (1.50 and 1.49 respectively). At the mid growth phase, 50% organic + 50% inorganic plants showed a trend towards higher values, followed by 100% organic (13.40 and 12.69 respectively) and by harvest 75% organic + innovative practices resulted in slightly higher CGR (8.43) compared to POP. Though not significant, CGR was favoured by organic treatments reflecting the impact of organic management practices during the critical growth period. Kumar *et al.* (2024) found that the crop growth rate of stevia showed an upward trend under organic manures, with increasing quantity of farmyard manure and vermicompost applied.

Relative Growth Rate (RGR) showed a tendency to decrease with crop age (Fig. 1). It was higher during second phase (3-6 MAP) than third phase (6-9 MAP). The treatments did not affect RGR significantly, though integrated practice (50% organic + 50% inorganic) produced relatively higher RGR at second phase, followed by 100% organic (26.24 and 24.94 respectively). Ahirwar *et al.* (2025) reported similar results in wheat. The RGR showed slight increase under 75% organic + innovative practices (5.45) compared to the other management options during the last phase. An increase of RGR was observed in all treatments from the first to the second growth period and a steep decrease was found from the second to the final growth stage. The trend in relative growth rate can be viewed as normal, as biomass production efficiency may decline

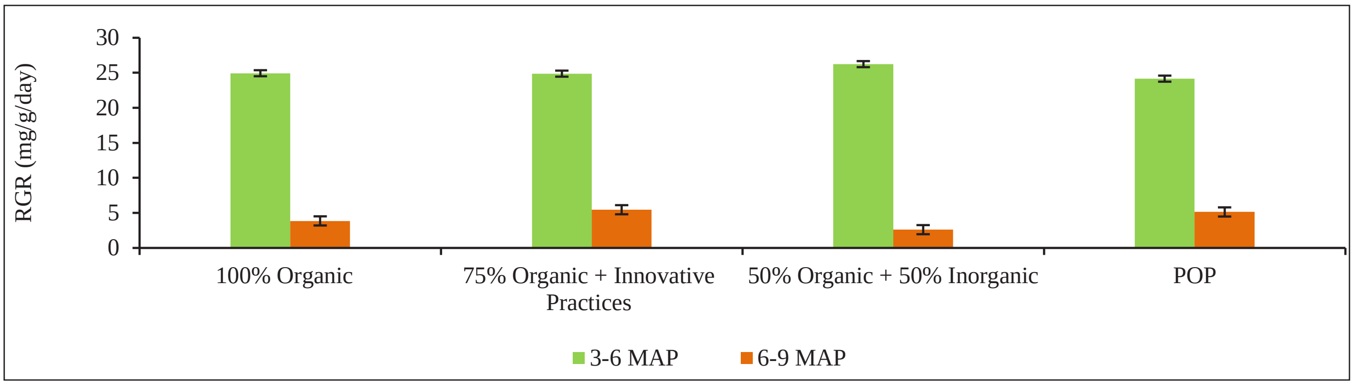


Fig. 1: Relative growth rate as affected by management options

over time due to plant senescence (Kumar *et al.,* 2024).

Tuber Bulking Rate (TBR) did not vary significantly, but during the initial and final phase, 75% organic + innovative practice showed comparatively higher TBR values (0.43 and 4.01 g/day respectively), while 50% organic +50% inorganic practices tended to be higher in mid phase (7.36 g/day). Among management options, 75% organic + innovative practices (3.54 g/day) resulted in significantly highest mean TBR. The higher TBR in first and final phases and the greater mean TBR might have contributed to a higher tuber yield in 75% organic + innovative practices. Similar trend of tuber bulking rate was documented by Seena Radhakrishnan *et al.* (2015). The higher LAI and CGR under organic management also led to efficient translocation of biomass to tuber resulting in higher TBR.

Harvest Index (HI) did not vary among the treatments at the initial stage, but 50% organic + 50% inorganic practices had slightly higher HI, followed by 75% organic + innovative practice (0.37 and 0.35 respectively). Management options varied significantly in HI at the last two phases of crop growth. 75% organic + innovative practices resulted in higher HI on a par with 50% organic + 50% inorganic practices at the mid growth phase (0.65 and 0.64 respectively). The harvest index (HI) at 9 MAP (0.61) was significantly highest in 75% organic + innovative practices (Fig. 2), which might have resulted in highest tuber yield in this management option. Farhad *et al.* (2009) noticed that applying poultry manure at varying levels in spring maize had a significant influence on the harvest index indicating that proper nutrient management through organic means can enhance crop performance.

The tuber yield was significantly highest in 75% organic + innovative practice (46.62 t/ha). This was followed by the 100% organic practices (41.37 t/ha) (Table 2). The mean weight of tubers, length and girth of tubers were also numerically higher under organic management options. The yield increase in 75% organic + innovative practices demonstrates effectiveness of integrating solid and liquid organic manures. Seena Radhakrishnan *et al.* (2022) reported significantly higher cassava yields under organic management practices compared to conventional systems. It has been conclusively proved that organic farming resulted in 10-20% higher yield over conventional farming in tropical tuber crops like elephant foot yam (*Amorphophallus paeoniifolius* (Dennst.) Nicolson), yams (*Dioscorea* spp.) and Chinese potato (*Plectranthus rotundifolius* (Poir.) Spreng) (Suja *et al.,* 2012; Suja and Sreekumar, 2014; Suja *et al.,* 2021). Mali *et al.* (2018) found that application of vermicompost along with biofertilizers resulted in higher growth and yield parameters. Joddar *et al.* (2025) noticed that combined application of vermicompost and

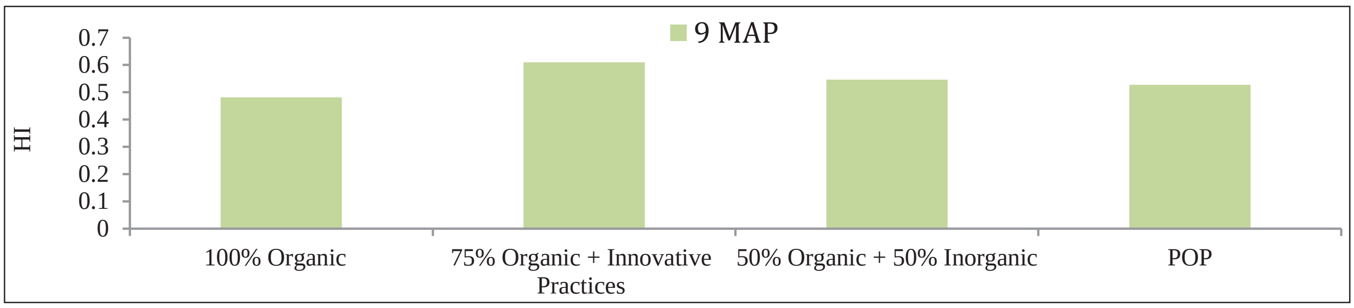


Fig. 2. Harvest index at 9 MAP as affected by management options

panchagavya facilitated higher grain yield in aromatic rice. These findings highlight the potential of organic inputs to boost crop output compared to conventional agricultural systems.

Table 2. Yield of cassava as influenced by management options

Management	Tuber yield (kg/plant)	Tuber yield (t/ha)
100% organic	3.35	41.37
75% organic + Innovative Practices	3.78	46.62
50% organic + 50% inorganic	3.32	41.01
package of practices	3.30	40.77
CD (0.05)	0.372	4.587

The yield of vegetables varied significantly among management options with 50% organic + 50% inorganic practice producing highest vegetable production (4.62 t/ha), followed by 100% organic and package of practices (4.61 and 4.16 respectively), which were on a par (Table 3). Among vegetables, okra produced highest yield. The combining vermicompost with synthetic fertilizers can enhance yield as integrated nutrient management balances nutrient availability with crop demand (Magar *et al.,* 2023). Management options did not impart significant variations in TEY, while 75% organic + innovative practices showed relatively higher system productivity. The vegetables x management options interactions indicated that highest tuber equivalent yield (TEY) was obtained in cassava intercropped with okra under 75% organic + innovative practices (63.92 t/ha), on a par with cassava + okra under 100% organic treatment (59.28 t/ha) (Table 4). The synergy of solid manure that offer slow-release nutrients and liquid manure that supplies quick-release nutrients together fulfill both immediate and long-term nutrient demands (Joddar *et al.*, 2025). This in turn leads to more balanced and sustained nutrient release throughout the crop cycle, resulting in higher yields, and greater overall system efficiency.

Table 3. System productivity under various management options

Management	Vegetable yield (t/ha)	Tuber equivalent yield (t/ha)
100% organic	4.61	48.30
75% organic + Innovative Practices	3.41	51.77
50% organic + 50% inorganic	4.62	48.32
package of practices	4.16	47.02
CD (0.05)	0.656	NS

Table 4. Interaction effect of vegetable intercrops and management options on vegetable yield and system productivity

Vegetables x management		Vegetable yield (t/ha)	TEY (t/ha)
	100% organic	2.69	41.82
Amaranthus	75% organic + inorganic practices	2.00	51.02
	50% organic + 50% inorganic	4.20	40.17
	package of practices	2.80	38.61
Okra	100% prganic	8.60	59.28
	75% oganic + innovative practices	6.24	63.92
	50% organic + 50% inorganic	7.26	56.54
	package of practices	7.77	48.73
Vegetable cowpea	100% organic	2.55	43.79
	75% organic + innovative practices	1.98	40.37
	50% organic + 50% inorganic	2.41	48.24
	package of practices	1.91	53.72
	CD (0.05)	1.560	6.529

The physical properties of soil, bulk density, particle density, water holding capacity and porosity were unaffected by various management options.

Various management options imparted significant effect on chemical properties of soil (Table 5). Among management options, 100% organic exhibited higher soil pH (4.45), on a par with POP (4.32) and 75% organic + innovative practices (4.16). Long-term experiments on organic farming undertaken at ICAR-CTCRI, Thiruvananthapuram (Suja *et al.*, 2012; Suja and Sreekumar, 2014; Suja *et al.*, 2017) strongly supports significant pH increase under organic management. The increase in pH can be attributed to the addition of green manure and other manures that plays a critical role in providing the soil surface with extra cations from deeper soil layers following the decomposition of nutrients. The electrical conductivity indicated no significant difference among treatments but organic managements showed a marginally higher value with 75% organic + innovative practices resulting in highest value, followed by 100% organic (0.39 and 0.35 respectively).

Soil organic C was significantly highest in 100% organic (1.78%). The incorporation of green manure cowpea along with effect of nutrient rich solid organic manures might have played a great role in increasing the organic carbon content. Ravisankar *et al.* (2016) found that inclusion of legumes in farming systems resulted in an average increase of 9.3% in soil organic carbon, improving from 0.75% to 0.82%. An increase in soil organic carbon after green manure incorporation, compost and organic matter addition were noticed in previous studies (Melero

Table 5. Major chemical properties of soil as influenced by management options

Management	pH	Elecrical conductivity (dS/m)	Organic carbon (%)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
100% organic	4.45	0.35	1.78	308.82	82.94	392.28
75% organic + innovative practices	4.16	0.39	1.53	226.97	77.83	368.85
50% organic + 50% Inorganic	3.94	0.34	1.40	202.07	58.34	335.09
package of practices	4.31	0.33	1.51	218.61	65.34	315.79
CD (0.05)	0.347	NS	0.192	24.567	7.200	NS

Table 6. Secondary and micronutrient status of soil as influenced by management options

Management	Exchangeable Ca (cmol/kg)	Exchangeable Mg (cmol/kg)	Available Fe (ppm)	Available Zn (ppm)	Available Cu (ppm)
100% organic	3.11	1.48	29.52	3.73	2.07
75% organic+ innovative practices	3.78	1.28	29.16	2.98	2.17
50% organic+ 50% inorganic	2.60	1.02	30.07	2.78	1.50
POP	2.47	1.03	30.87	2.17	1.51
CD (0.05)	0.208	0.236	NS	0.378	0.271

et al., 2008; Gurudivya *et al.*, 2025). Higher organic C status of organic plots might be attributed to addition of green manure cowpea along with poultry manure and vermicompost.

Among management options, 100% organic treatment resulted in significantly highest soil available N (308.82 kg/ha). Higher available N status may be due to higher N content in the organic manures particularly poultry manure, and green manure. Gurudivya *et al.* (2025) observed increase in available nitrogen and phosphorus content through green manuring. Available P content was highest in 100% organic management (82.94 kg/ha) on a par with 75% organic + innovative practices (77.83 kg/ha). The increase in P can be due to the application of vermicompost that can significantly increase phosphorous-use efficiency and further enhance the ability of soil to recycle essential micronutrients (Nieto-Cantero *et al.* 2025). Though available K content was not influenced significantly, it was tended to be higher under 75% organic + innovative practice (368.85 kg/ha).

Significantly higher exchangeable Ca (3.78 cmol/kg) was in 75% organic + innovative practices. Higher levels of exchangeable Mg were in 100% organic practices (1.48 cmol/kg) on par with 75% organic + innovative practices (1.28 cmol/kg) (Table 6). The Fe content was not significantly affected by the various management options. 100% organic management resulted in significantly higher values of available Zn (3.73 ppm). Available Cu was higher in 75% organic + innovative practices (2.17 ppm) on a par with 100% organic treatment (2.07 ppm). Studies by Kwiatkowski and Harasim (2020) also observed comparable increase in pH, organic C, available N, Mg and Zn content in the organically managed soil compared to the conventional system. According to the study by Melero *et al.* (2008) soils under organic fertilization showed improvement in soil fertility. The sustained use of organic amendments play a critical role in boosting the soil properties in the long term and increase its plant available micronutrient contents (Zhang *et al.,* 2015).

CONCLUSIONS

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.

REFERENCES

Ahirwar H, Kulhare P S, Tagore G S, Prajapati S S and Singh V. 2025. Effects of organic and inorganic fertilizers on soil properties, nutrient dynamics, and maize yield (*Zea mays* L.). *International Journal of Plant and Soil Science* **37**(1): 384-92.

Almunqedhi B M, Alfarhan A, Muharram A A and Mohammed N. 2025. Sustainable potato farming: The impact of poultry manure on growth and yield. *Applied Ecology and Environmental Research* **23**(3): 3929-37.

Bayata A. 2019. Review on nutritional value of cassava for use as a staple food. *Science Journal of Analytical Chemistry* **7**(4): 83-91.

Brooker R W, Bennett A E, Cong W F, Daniell T J, George T S, Hallett P D, Cathy H, . Iannetta P P M, Jones H G, Karley A J and Li L. et al. 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist* **206** (1): 107–17.

Devasenapathy P, Senthilkumar G and Shanmugam P M. 2009. Energy management in crop production. *Indian Journal of Agronomy* **54**(1): 80-90.

Farhad W, Saleem M F, Cheema M A and Hammad H M. 2009. Effect of poultry manure levels on the productivity of spring maize (*Zea mays* L.). *The Journal of Animal and Plant Sciences* **19**(3): 122-25.

Gupta R P and Dakshinamoorthy C. 1980. *Procedures for Physical Analysis of Soil and Collection of Agrometeorological Data*. Indian Agricultural Research Institute, New Delhi.

Gurudivya P, Sundarrajan R V, Sankar C, Usha Nandini P M and Dharani J. 2025. Improving soil health and weed control through Dhaincha (*Sesbania aculeata*) green manuring under semi-arid conditions. *Journal of Advances in Biology and Biotechnology* **28**(8): 148-55

Hunt R. 1982. *Plant Growth Curves: the Functional Approach to Plant Growth Analysis*, Arnold Publishers, London.

Joddar P, Patra P, Karki S, Hoque A, Ahmed A and Paramanik B. 2025. Performance of liquid organic formulations in combination with vermicompost on yield, quality and economics of aromatic rice (*Oryza sativa*). *Indian Journal of Agronomy* **70**(2): 137-42

Kumar P M, Sindhu P V, Prameela P and Savitha A. 2024. Growth rate and nutrient uptake of *Stevia rebaudiana* bertoni as influenced by organic manures in laterite soils of Kerala, India. *Journal of Experimental Agriculture International* **46**(10): 442-49.

Kwiatkowski C A and Harasim E. 2020. Chemical properties of soil in four-field crop rotations under organic and conventional farming systems. *Agronomy* **10**(7): 1045.

Lithourgidis A S, Dordas C A, Damalas C A and Vlachostergios D N. 2011. Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science* **5** (4), 396–410.

Magar S K, Poudel B, Dhungana R, Rawal S, Thapa S, Bhusal K K and Malla S. 2023. Effect of integrated nutrient management on growth, yield, and soil nutrient status in okra (*Abelmoschus esculentus* cv. Arka Anamika). *Archives of Agriculture and Environmental Science* **8**(1): 49-54.

Mali D L, Singh V, Sarolia D K, Teli S K, Chittora A and Dhakar R. 2018. Effect of organic manures and bio-fertilizers on growth and yield of radish (*Raphanus sativus* L.) cv. Japanese white. *International Journal of Chemical Studies* **6**(2): 1095-98.

Melero S, Madejón E, Herencia J F and Ruiz J C. 2008. Effect of implementing organic farming on chemical and biochemical properties of an irrigated loam soil. *Agronomy Journal* **100**(1): 136-44.

Nedunchezhiyan M, Suja G and Ravi V. 2022. Tropical root and tuber crops based cropping systems – a review. *Current Horticulture* **10**(1); 14-22.

Nieto-Cantero J, García-López A M, Recena R, Quinter, J M and Delgado A. 2025. Recycling manure as vermicompost: Assessing phosphorus fertilizer efficiency and effects on soil health under different soil management. *Journal of Soil Science and Plant Nutrition* **25**(2): 5046-61.

Page A L, Miller R H and Keeney D R. 1982. *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*. Agronomy series No.**9**, American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA, 1159 p.

Ravi V, Suja G, Saravanan R and More S J. 2021. Advances in cassava based multiple cropping systems. *Horticultural Reviews* **48**: 153-232.

Ravisankar N, Ansari M A, Panwar A S, Aulakh C S, Sharma S K, Suganthy M, Suja G and Jaganathan D. 2021. Organic farming research in India: Potential technologies and way forward. *Indian Journal of Agronomy* **66**: S142-S162.

Ravisankar N, Singh P, Mishra R P, Prusty A K, Shamim M, Singh R, Tripathi D and Mohan B. 2016. *Annual Report of AICRP on Integrated Farming System*. ICAR-Indian Institute of Farming Systems Research Modipuram, Meerut, 258 p.

Seena Radhakrishnan A R, Suja G and Anil A T. 2015. Organic vs conventional management in cassava: Growth dynamics, yield and soil properties. *Journal of Root Crops* **39**(2): 93–99.

Seena Radhakrishnan A R, Suja G and Sreekumar J. 2022. How sustainable is organic management in cassava? Evidences from yield, soil quality, energetics and economics in the humid tropics of South India. *Scientia Horticulturae* **293**: 110723.

Soni R, Gupta R, Agarwal P and Mishra R. 2022. Organic farming: A sustainable agricultural practice. *Vantage: Journal of Thematic Analysis* **3**(1): 21-44.

Suja G, Byju G, Jyothi A N, Veena S S and Sreekumar J. 2017. Yield, quality and soil health under organic vs conventional farming in taro. *Scientia Horticulturae* **218**: 334-43.

Suja G and Sreekumar J. 2014. Implications of organic management on yield, tuber quality and soil health in yams in the humid tropics. *International Journal of Plant Production* **8**(3): 291–309.

Suja G, Sreekumar J, Byju G, Veena S S, Sunitha S, Ramesh V, Maria C.L and Raj R K. 2021. Organic management of Chinese potato: Growth, yield, quality, soil health, and economics. *International Journal of Vegetable Science* **27**(6): 585–603. https://doi.org/10.1080/19315260.2021.1907829

Suja G, Sreekumar J, Sunitha S and Jacob John. 2025. Evaluation of short-duration cassava (*Manihot esculenta* Crantz) cropping system for profitability, energy efficiency and soil restoration. *Current Horticulture* **13**(1): 35-41.

Suja G, Sundaresan S, Susan John K, Sreekumar J and Misra R S. 2012. Higher yield, profit and soil quality from organic farming of elephant foot yam. *Agronomy for Sustainable Development* **32**:755–64. doi:10.1007/s13593-011-0058-5.

Velten S, Leventon J, Jager N and Newig J. 2015. What is sustainable agriculture? A systematic review. *Sustainability* **7**(6): 7833-65.

Willey R W. 1979. Intercropping-its importance and research needs. *Field Crop Abstracts* **32**: 1–10.

Zhang S, Li Z and Yang X. 2015. Effects of long-term inorganic and organic fertilization on soil micronutrient status. *Communications in Soil Science and Plant Analysis* **46**(14): 1778-90.

Current Horticulture **14**(2): 107-109, April–June 2026
DOI: 10.5958/2455-7560.2026.00028.1
Received: 5 October 2025; Accepted: 12 June 2026

Study of fruit-borer *Deudorix (Virachola) isocrates* on pomegranate (*Punica granatum*) and its fluctuation through abiotic stress

Suresh Kumar Jat[1*], Anchal Sharma[1] and Ashok Choudhary[2]

[1]*College of Horticulture & Forestry, Jhalawar, Raj. (Agriculture University, Kota)*

Abstract

The experiment was conducted to study the relation between the occurrence of mature and immature stages of *Deudorix isocrates* (Lepidoptera: Lycaenidae), on pomegranate (*Punica granatum L.*) plant phenology, and changes in population due to abiotic stress at College of Horticulture & Forestry, Jhalawar, during 2022-23. The population dynamics of *Deudorix isocrates* larvae on fruits was monitored during the *kharif* seasons of 2022 and 2023, under different climatic factors, such as mean temperature (°C), relative humidity (%), and rainfall (mm). The data showed that pomegranate fruit was most preferential host plant for fruits borer, serving as the prime host plant when other potential host plants were not available during certain developmental stages of the pest. The pest population reached to peak during 36th standard meteorological week (SMW) during both years. Statistical analysis indicates a positive, but non-significant, correlation with temp (x_1 = 0.32) and negative, non-significant correlations with relative humidity (x_2 = -0.47) and rainfall (x_3= -0.35) during 2022. In contrast, during 2023, pest exhibited a negative, non-significant correlation with temperature (x_1 = -0.23), and positive, non-significant correlations with both relative humidity (x_2= 0.31) and rainfall (x_3= 0.36)

Key words: Abiotic stress, *Deudorix (Virachola) isocrates* Host plant, Fruit, borer

Pomegranate (*Punica granatum* L.) is a prominent fruit crop in India. Its cultivation is significantly affected by a diverse range of insect pests, lepidopteran species being most damaging ones. These pests severely impact fruit quality and marketability (Abd-Ella, 2015). In India alone, over 50 species of insect pests have been reported infesting pomegranate (Butani, 1979; Balikai, 2000). Among these, the most damaging is fruits-borer butterfly, *Deudorix (Virachola) isocrates* Fabricius, which can cause damage on more than 50% of developing fruits (Balikai *et al.,* 2011). The early larval stage of *V. isocrates* bores into fruits, feeding on seeds and the pulp. The entry holes created by its larvae also serve as an infection site for other pathogens, resulting in extensive fruit rotting (Balikai *et al.,* 2009; Abazaid *et al.,* 2021). Having a wide host preference, *V. isocrates* is considered to as the most destructive pest of pomegranate, causing 65–70% yield loss globally (Gupta and Dubey, 2005; Kumar, 2010; Kumar *et al.,* 2017). Therefore, to understand the phenological stages of pomegranate in regard to pest infestation was studies.

MATERIALS AND METHODS

Field trials were conducted at College of Horticulture and Forestry, Jhalawar, during *kharif* seasons of 2022 and 2023 to assess the seasonal occurrence and population dynamics of insect pests associated with pomegranate fruit, with a specific focus on fruits-borer *Deudorix (Virachola) isocrates* in Bhagwa variety of pomegranate.

Corresponding author : suresh@aukota.org
[2]College of Horticulture, Durgapura, Jaipur (SKNAU, Jobner)

Fruit borer population were documented at weekly intervals during fruiting season. For sampling, five distinct sites within the orchard, representing cardinal directions (North, South, East, West, and Centre), were selected. From each site, five plants were randomly chosen each week to assess the number of healthy and infested fruits. Infestation was identified by the presence of active bore holes in fruits, which indicated larval activity. The population of fruit-borer larvae was studied based on visible symptoms. Meteorological data, including ambient temperature (°C), relative humidity (RH%), and rainfall (mm), were also collected to analyse their relationship with pest occurrence. Coefficient of correlation was employed to determine the statistical relationship between environmental parameters and pest population dynamics.

RESULTS AND DISCUSSION

The early appearance of fruit-borer was observed during second week of August (32nd Standard Meteorological Week [SMW]) with a mean larval population of 1.00 and 1.50 larvae/ five fruits during 2022 and 2023, respectively (Tables 1 and 2). The pest population subsequently increased, reaching its peak during first week of September (36th SMW), with a maximum mean population of 6.50 and 7.50 larvae/ five fruits during 2022 and 2023, respectively. Following this peak, the population began to decline, with a notable reduction documented by fourth week of September (39th SMW), and complete disappearance by the second week of October during both years.

Table 1: Influence of abiotic factors on seasonal incidence of pomegranate fruit-borer during *kharif* 2022

Standard Meteorological Weeks (SMW)	Date of Observation	Abiotic factor			Fruit borer (per 5 fruits)
		Mean Temp. (°C) (X_1)	Mean R.H. (%) (X_2)	Total Rainfall (mm) (X_3)	
31	30 July -5Aug	26.05	73.2	24	00
32	6 Aug-12 Aug	27.05	78.65	49	1.5
33	13 Aug-19 Aug	25.2	81.75	116	3.9
34	20 Aug-26 Aug	25.75	88.35	263	2.6
35	27 Aug-2 Sept	28.45	59.35	2	3.6
36	3 Sept -9 Sept	27.95	67.7	20	6.6
37	10 Sept-16 Sept	27.2	75.95	73	**3.5**
38	17 Sept - 23 Sept	26.2	74.4	42	1.6
39	24 Sep – 30 Sep	26.05	60.45	0	1.00
Seasonal mean		26.66	73.31	589.00	3.04
Coefficient of correlation (r) for population and mean atm. temperature					0.32
Coefficient of correlation (r) for population and mean relative humidity					-0.47
Coefficient of correlation (r) for population and total rainfall					-0.35

Table 2: Influence of abiotic factors on seasonal incidence of pomegranate fruit-borer during kharif 2023

Standard Meteorological Weeks (SMW)	Date of observation	Abiotic factor			Fruit-borer (per 5 fruits)
		Mean temp. (°C) (X_1)	Mean R.H. (%) (X_2)	Total rainfall (mm) (X_3)	
31	30 July -5Aug	27.5	89.0	13.0	00
32	6 Aug-12 Aug	27.5	78.0	3.0	1
33	13 Aug-19 Aug	27.5	86.0	7.0	1.9
34	20 Aug-26 Aug	28.0	90.5	126.0	3.6
35	27 Aug-2 Sept	28.0	85.5	0.0	5.6
36	3 Sept -9 Sept	27.5	77.0	43.0	**7.5**
37	10 Sept-16 Sept	28.0	93.0	134.0	4.9
38	17 Sept - 23 Sept	28.5	81.5	14.0	2.3
39	24 Sep – 30 Sep	28.50	60.00	0.0	1.50
Seasonal Mean		27.81	85.06	340.00	3.54
Coefficient of correlation (r) for population and mean atm. temperature					-0.23
Coefficient of correlation (r) for population and mean relative humidity					0.31
Coefficient of correlation (r) for population and total rainfall					0.36

The fruits-borer infestation was more severe in 2023 than in 2022. This hike may be due to higher mean relative humidity, slightly elevated atmospheric temperature, and lower cumulative rainfall during the critical infestation period in 2023. Specifically, during the peak infestation period, the average temperature, relative humidity, and rainfall were 27.55°C, 67.7%, and 20.0 mm during 2022, compared to 27.50°C, 77.0%, and 43.0 mm during 2023. The pest showed positive non-significant correlation with temperature (x_1 = 0.32) and negative non-significant correlation with humidity (x_2 = - 0.47) and rainfall (x_3 = -0.35) during 2022. In 2023 the pest showed negative non-significant correlation with temperature (x_1 = -0.23) and positive non-significant correlation with humidity (x_2 = 0.31) and rainfall (x_3 = 0.36).

These findings bring into line with those of Haseeb and Sharma (2007). Similarly, Kumari *et al.* (2011) observed maximum infestation during third week of August. However, local variations have also been noted. These regional discrepancies may be due to differences in fruiting phenology and local climatic conditions, as also suggested by Shevale and Khaire (1999). Regarding larval load per fruit, Uma Shankar *et al.* (2007) documented an average of 6.75 caterpillars/ fruit, while Balikai *et al.* (2011) observed up to 8 caterpillars in a single fruit. In contrast, Singh (1973) recorded a maximum of 4 larvae/ fruit.

CONCLUSION

The study confirmed that fruits-borer, *Deudorix (Virachola) isocrates* was most persistent and destructive insect pest affecting pomegranate during both *kharif* seasons of 2022 and 2023. The initial emergence of larvae was observed during the second week of August (32nd Standard Meteorological Week [SMW]) in both years. Peak infestation levels were recorded during first week of September (36th SMW), indicating a consistent seasonal pattern of occurrence. Despite comprehensive monitoring and correlation analysis, no statistically significant relationship was observed between fruits borer population and weather parameters (temperature, relative humidity, and rainfall) during the study.

REFERENCES

Abazied, M.A. 2021. Survey and Abundance of Major Insect Pests on Pomegranate.

Abd-Ella, A.A. 2015. Efficacy of emamectin benzoate, pyridalyl and methoxyfenozide on pomegranate butterfly, *Virachola livia* (Klug) (Lepidoptera: Lycanidae) in cultivated and reclaimed lands. *Journal of Phytopathology and Pest Management,* 32-42.

Balikai R A, Kotikal Y K and Prassana P M 2011. Status of pomegranate pests and their management strategies in India. *Acta Horticulturae,* **8**: 569-84.

Balikai, RA. 2000. Status of pomegranate pests in Karnataka. *Pest Management Horticultural Ecosystem,* **6**(1):65-66.

Butani DK. 979. Pests of pomegranate. Insects and fruits. Periodical Expert Book Agency, Delhi, pp 228.

Deepak Sangwan., J. R. Sharma., Manish Kumar., Hardeep., Vikalp and Rajesh Mor 2025. Performance of Different Pomegranate Cultivars Under Semi-Arid Condition of Haryana. *Current Horticulture* **13** (4): 74-77.

Gupta D, Dubey JK. 2005. Bioefficacy of some insecticides against pomegranate fruit borer, *Deudorix epijarbas* (Moore). *Acta Horticulturae* **696**:419-21.

Haseeb M and Sharma S [2007]. Studies on incidence and crop losses by fruit borer *Deudorix isocrates* on Guava. *Acta Horticulture* **735**: 489-92.

Kumar KP, Kamala Jayanthi PD, Naik S Onkara, Verghese A, Chakravarthy AK. 2017. Biology of Anar Butterfly, *Deudorix isocrates* (Fab.) (Lycaenidae: Lepidoptera) on Pomegranate, *Punica granatum* L. *International Journal of Pure and Applied Bioscience* **5**(1):498-503.

Kumar N. 2010. Evaluation of some insecticides against pomegranate fruit borer, *Deudorix epijarbas* (Moore).

Thesis, Dr Y S Parmar University of Horticulture and Forestry, Solan.

Kumari D A, Lakshmi B K M, Suresh Kumar T and Reddy G S 2011. Population dynamics of major pests of pomegranate in Central Telagangana Zone of Andhra Pradesh. *Acta Horticulture* **890**: 585-87.

Shevale B S and Khaire V M 1999. Seasonal abundance of pomegranate butterfly, *Deudorix isocrates*. *Entomon,* **24**: 27-31.

Singh N 1973. Biological studies on the habits and behavior of anar butterfly, *Virachola isocrates* Fabricius. Thesis submitted to Himachal Pradesh University Agricultural Complex, College of Agriculture, Solan.

Uma Shankar, Kaul V and Rai S 2007. New record of anar fruit borer, *Deudorix isocrates* (Fabricus) on Aonla in Jammu. *SKUAST- Journal of Research* **6**: 291- 94.

Current Horticulture **14**(2): 110-112, April–June 2026
DOI: 10.5958/2455-7560.2026.00029.8
Received: 19 January 2026; Accepted: 19 April 2026

Natural greenhouse: a biologically engineered, low-cost and climate-resilient protected cultivation system

Rajaram Tripathi

Maa Danteshwari Herbal Farms and Research Centre Kondagaon, Bastar, Chattisgarh 494 226, India

Abstract

Protected cultivation has emerged as an important approach for enhancing crop productivity, quality, and income in Indian agriculture. However, the widespread adoption of conventional polyhouse technology remains limited due to its high capital cost, dependence on synthetic materials, recurring energy requirements, vulnerability to extreme weather events, and short functional lifespan. Therefore, a farmer-led, field-validated and biologically-engineered natural greenhouse has been developed and demonstrated to farmers at Maa Danteshwari Herbal Farms, Kondagaon, Bastar, Chhattisgarh, India. The natural greenhouse is based on a multi-tier living architecture integrating a fast-growing nitrogen-fixing tree species, locally known as Australian teak (*Acacia* spp.), with a high-yielding black pepper variety (MDBP-16). The system functions as a self-regulating protected cultivation unit, creating a favourable microclimate through canopy-mediated light diffusion, temperature moderation, moisture conservation, and continuous organic nutrient cycling. Unlike conventional polyhouses, it operates without plastic structures, artificial climate control, or external energy inputs.It cost, approximately ₹ 1.0–1.5 lakh per acre, compared to nearly ₹ 40 lakh per acre for a standard polyhouse. The natural greenhouse remains productive for 25–30 years. Independent scientific validation by senior scientists of the ICAR–Indian Institute of Spices Research (IISR), Kozhikode, Kerala, and its regional centre at Madikeri, Karnataka, confirmed black pepper yields of 8–10 kg dry berries per vine, far exceeding the national average of 1.5–2.0 kg. In addition to annual crop income, the system generates long-term timber value, enhances soil health, and contributes to carbon sequestration. The study establishes the natural greenhouse as a scientifically credible, economically viable, and ecologically regenerative alternative to conventional protected cultivation, with significant potential for replication in suitable agroclimatic regions globally

Key words: Natural greenhouse, Protected cultivation, Australian teak, Black pepper, Climate-resilient agriculture, Indigenous innovation

Protected cultivation has emerged as an important technological intervention for enhancing crop productivity, quality, and resource-use efficiency under diverse agroclimatic conditions. By modifying crop microenvironment—particularly temperature, humidity, light, and carbon dioxide concentration—greenhouse and polyhouse systems enable year-round production and protection from adverse climatic factors such as heavy rainfall, strong winds, and temperature extremes, and pest incidence. These systems therefore play crucial role in stabilizing production and ensuring consistent supply of high-value horticulture crops, especially in regions where open field cultivation is constrained by environmental variability (Mhada 2024) Despite these advantages the whispered widespread adoption of conventional greenhouse technologies remain limited, particularly by small and marginal farmers. (Jhadav and Rosentrators, 2017). To overcome these constraints, considerable research has been directed towards the development of low-cost protected cultivation system using logically available materials and passive environmental control. For instant successful production of capsicum (*Capsicum annuum* L.) under such system has enhanced yield, extended harvesting duration, and improve quality attributes under mild winter conditions (Kumar and Verma 2009).Similarly optimisation of agro-techniques under low-cost polyhouse conditions has resulted in improved growth, flowering, and yield of chrysanthemum (*Chrysanthemun Ap.*), indicating the effectiveness of partial micro climate regulation in such systems (Janakarin *et al.,* 2006). Further evidence suggest that even simple greenhouse modifications can significantly enhance yield of tomato (*Lycopersicum esculentum* L.). (Ganesan, 2003). Likewise, studies on ornamental crops such as gerbera (Gerbera sp.) have demonstrated that optimized fertigation and nutrient management under protected conditions significantly enhanced plant growth and flower yield, emphasizing the importance of controlled environment in improving crop performance (Sujatha *et al.,* 2002). However despite, these advancements, existing protected cultivation system both conventional and low-cost still face several limitations. These include inadequate regulation of extreme environmental conditions, dependence on external inputs for nutrient and water management, and variability in performance across different agro-climatic regions.

Corresponding author : rajaramherbal@gmail.com

Moreover, most systems relay on static structural designs that do not dynamically respond to environmental fluctuations, thereby limiting their efficiency and resilience under changing climatic scenarios (Bonachela *et al.,* 2024). In this context, there is an increasing need to explore alternative approaches that integrate ecological principles with production systems to achieve sustainable intensification. Nature-based and biologically-driven systems offer the potential to regulate microclimate, enhance nutrient cycling, improve soil health, and support biodiversity, thereby reducing dependence on external inputs while maintaining productivity. Such approaches align with emerging paradigms of climate-resilient and resource-efficient agriculture (Jhadav and Rosentrater, 2017).

The concept of a natural greenhouse represents one such innovative approach, wherein living plant architecture is utilized to create a self-regulating microenvironment in place of synthetic structures. By integrating fast-growing tree spices with climbing crops, this system aims to provide functional benefits similar to conventional protected cultivation-like as light diffusion, temperature moderation, and moisture conservation. Unlike conventional polyhouses, this biologically engineered system relies on natural processes r,ather than atificial inputs offering a long-term and climate-resilient alternative for sustainable production.

MATERIALS AND METHODS

The natural greenhouse is established through systematic plantation of fast-growing Australian teak (*Acacia* spp.) at designed spacing. These trees serve multiple functions: they act as permanent life supports for black pepper vines create a vertically stratified canopy, and regulate the farm microclimate. Black pepper vines are trained vertically on these trees enabling true vertical farming extending up to 20 feet in early years and progressively higher with tree growth.

The tree canopy provides approximately 60–70 per cent diffused shading, comparable to the light filtration achieved in polyhouses. Unlike static plastic films, the shade dynamically shifts with solar movement, extending the effective photosynthetic period and reducing photoinhibition. Field observations show that the internal temperature within the Natural Greenhouse remains 3–4°C lower than ambient temperatures during summer and relatively warmer during winter.

RESULTS AND DISCUSSION

A defining feature of natural greenhouse system is the integration of biological processes for nutrient supply and ecosystem regulation. The use of *Acacia* spp. as a structural component enables biological nitrogen fixation through symbiotic associations with Rhizobium, providing a continuous and natural source of nitrogen. This process reduces or eliminates the need for synthetic fertilizers, aligning with findings from protected cultivation systems where optimized nutrient management significantly enhances plant growth and productivity (Sujatha *et al.,* 2002). In addition, seasonal leaf litter contributes to *in-situ* organic matter accumulation, improving soil organic carbon, enhancing microbial activity, and increasing soil moisture retention-factors known to support sustained crop performance under low-input systems.

The multi-tier vegetation structure further contributes to ecological intensification by creating a functional agroecosystem. The canopy-mediated microclimate moderates temperature and light, similar to microenvironmental regulation observed in low-cost polyhouse systems, which significantly influence crop growth and yield (Janakiran *et al.,* 2006). Furthermore, the system promotes biodiversity, particularly avian populations, which play a role in natural pest regulation. Bird activity also contributes to nutrient recycling through droppings, thereby supplementing soil fertility. The dense canopy cover, combined with organic mulching from litter fall, reduces evapotranspiration losses and improves water-use efficiency. Such microclimatic buffering and resource conservation are consistent with observations in protected cultivation systems, where controlled environments enhance crop performance and reduce abiotic stress (Mhade *et al.,* 2024).

The performance of black pepper under the natural greenhouse system has been independently validated by scientists from ICAR–Indian Institute of Spices Research (IISR), Kozhikode, Kalicut, Kerala, and its regional centre at Madikeri. Their findings, (Spice India, April 2023), provide empirical support for productivity and quality advantages of this system .The yields, of 8–10 kg dry berries/vine under organic management is substantially higher than the national average of 1.5–2.0 kg/vine. Such enhanced productivity can be attributed to favourable microclimatic conditions, improved nutrient availability, and reduced physiological stress. These observations are in agreement with studies on protected cultivation, where modification of environmental parameters significantly improves crop yield and quality. For instance, greenhouse-based studies on vegetable crops have demonstrated improved biochemical attributes and productivity due to better regulation of temperature, humidity, and light (Jadhav and Rosentrater, 2017).

In addition to higher yields, the system produces berries of superior quality with strong vine vigour and better market acceptance. The produce meets exports quality standards, indicating its commercial viability. Importantly, the system has demonstrated adaptability to non-traditional pepper-growing regions such as Bastar, suggesting that microclimate modification through biological structures can expand the geographical scope of crop cultivation (Ganesan, 2002).

The greenhouse system offers significant economic advantages over conventional protected cultivation structures. With an establishment cost of approximately ₹1.0–1.5 lakh per acre, it is substantially more affordable than conventional polyhouses, whose high capital requirements are a major barrier to adoption (Jadhav and Rosentrater, 2017). The system generates annual gross returns of up to ₹5 lakh per acre from black pepper alone, indicating strong economic viability. In addition to annual income, the inclusion of *Acacia* trees provides long-term capital gains through timber production, comparable to high-value species such as teak and mahogany. This dual-income model—combining annual crop yield with long-term timber value—enhances financial stability and resilience for farmers. Unlike conventional polyhouses, which have a limited lifespan and generate plastic and metal waste, the natural greenhouse remains productive for 25-30 years. This extended lifespan significantly improves cost-benefit ratio and reduces environmental burden, aligning with the need for sustainable and low-input agricultural systems.

The such adaptability is comparable to low-cost protected cultivation systems, which have been successfully implemented across varied environments to improve crop performance and livelihood outcomes (Mahde *et al.,* 2024). However, Natural Greenhouse extends this concept further by replacing synthetic structures with biological components, thereby reducing dependence on external inputs and enhancing ecological sustainability.

Conclusion

The natural greenhouse represents a scientifically validated, farmer-led innovation that advances the concept of protected cultivation through a biologically engineered approach. By integrating *Acacia* (Australian teak) with high-performing black pepper within a living structural framework, the system effectively regulates microclimate, enhances nutrient cycling, and supports sustained crop productivity without reliance on synthetic inputs.

ACKNOWLEDGEMENTS

The author expresses gratitude to nature, farming communities, and the scientists of the ICAR-Indian Institute of Spices Research, Kalicut, for their independent evaluation and constructive insights. The contribution of tribal farmers of Bastar in adopting and refining this model is gratefully acknowledged.

REFERENCES

Spices Board of India. 2023. Black Gold: Culture of Bastar Region. *Spice India*, April 2023, Vol. **36**, No. (4).

NHB, Gurgaon. National Horticulture Board. Guidelines for Protected Cultivation Structures in India.

FAO. Climate-Smart Agriculture Sourcebook. Food and Agriculture Organization of the United Nations.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*.

Sujatha K, Gowda JN, Khan MM.2002. Effects of different fertigation levels on gerbera under low cost greenhouse. *Journal of Ornamental Horticulture* **5**: 54–59.

Bonachela S, Granados M R, Hernández J, López J C and Magán J.2024. Combined passive heating systems in Mediterranean low-cost greenhouse cucumber crops. *Agronomy* **14:** 374.

Ganesan M.2002. Comparative evaluation of low cost greenhouse and its effect on the yield and quality of two varieties of tomato (Lycopersicon esculentum Mill). *Indian Agriculture* **46:** 161–68.

Jadhav H T, Rosentrater K A 2017. Economic and environmental analysis of greenhouse crop production with special reference to low cost greenhouses: A review. *ASABE Annual International Meeting*: 1.

Janakarin T, Mahantesh, Murgod I and Prabhakar BS 2006. Standardization of agro-techniques for production of chrysanthemum under low cost polyhouse. *Acta Horticulturae* **710**: 321–28.

Kumar M and Verma V 2009. Bell pepper (Capsicum annuum L.) production in low cost naturally-ventilated polyhouses during winters in the mid hills of India. *Acta Horticulturae* **807**: 389–94.

Mhade RR, Jadhav HT, Malathi AN.2024. A comprehensive review of low-cost polyhouses: Innovations and impacts on horticultural produce. *Agricultural Research Journal* **61**: 322–31.

Current Horticulture **14**(2): 113-116, April–June 2026
DOI: 10.5958/2455-7560.2026.00030.9
Received: 22 September 2025; Accepted: 17 June 2026

Performance evaluation of onion (*Allium cepa*) genotypes for growth, yield, quality and pest incidence in Dharwad, Karnataka, India

Kushal[1*], Kurubar, A R[1], Shashidhar, T R[2], Vittal Mangi[2] and Vanishree[2].

[1]*University of Agricultural Sciences, Raichur, Karnataka -584 101, India*

Abstract

The performance of 50 onion (*Allium cepa* L.) genotypes for growth, yield, bulb quality and pest incidence evaluated during the *rabi* 2023-24 and 2024-25 at University of Agricultural Sciences, Dharwad, Karnataka. Pooled analysis of variance (ANOVA) revealed significant genotypic differences for all traits in both seasons. High yielding genotypes were NHRDF Red-2 (50.89 tonnes/ha in 2024-25), NHRDF Red-4 (47.72 tonnes/ha) and Bhima Raj (46.42 tonnes/ha). Genotype Telagi-L exhibited desirable thin neck thickness (0.52 cm), while DOGR-1771 showed high dry matter content (18.42 g). Low pest incidence was observed in NHRDF Red-4 and NHRDF Red-2 (0.50% and 0% purple blotch, respectively) and Arakera local (0.51 thrips/plant). These findings highlight superior genotypes for cultivation and potential use in breeding programmes in similar agroclimatic regions.

Key words: Genotypes, Yield attributes, Bulb quality, Pest incidence, *Rabi*.

Onion (*Allium cepa* L.), a biennial herb of Alliaceae family, is a critical vegetable crop globally, ranking fourth among consumable vegetables after tomato, cabbage, and watermelon (Best, 2000). In India, onion cultivation spans 1.54 million ha., producing 24.21 million tonnes with a productivity of 16.10 tonnes/ha, while Karnataka contributes 0.25 million hectares with 2.05 million tonnes at 14.17 tonnes/ha (MA&FW New Delhi, 2024). Despite its economic importance, India's productivity lags behind countries like the USA (55.95 tonnes/ha) and the Netherlands (49.70 tonnes/ha), largely due to limited adoption of high-yielding hybrids and region-specific genotypes (Gupta *et al.*, 2024).

Onion crop is affected by its photo-thermo sensitivity, requiring specific temperature (12.8–25.0°C) and day length (12–13 hours for *rabi* varieties) for optimal growth and bulb development (Thamburaj and Singh, 2019). Genotypic variation in traits such as plant height, bulb yield, total soluble solids (TSS), and pest resistance is critical for selecting suitable cultivars for specific regions (Malik *et al.*, 2024; Rani *et al.*, 2024). Therefore, performance of 50 onion genotypes over two *rabi* seasons (2023-24 and 2024-25), focusing on growth, yield, bulb quality, and pest incidence to identify superior genotypes for cultivation was evaluated at Dharwad.

MATERIALS AND METHODS

The experiment was conducted at Horticultural Research Station, University of Agricultural Sciences, Dharwad (15°26'N, 75°07'E, 678 m ASL) during *rabi* seasons 2023-24 and 2024-25. The soil was medium black clay with a pH of 7.5. A randomized complete block design with two replications was used. Seedlings were raised in nursery beds. The seedlings of 60 days old were transplanted at into plots of 1 m × 1.2 m at 15 cm × 10 cm spacing. Fifty genotypes, were collected from institutions. These included red, light red, dark red, and white bulb types. Five plants per replication were sampled at maturity (120–150 days post-transplanting). Pooled ANOVA was performed using OPSTAT software, with critical difference (CD) calculated at 5% significance. Weather conditions varied between seasons. In 2023-24, total rainfall was 510.70 mm, with average maximum and minimum temperatures of 31.85°C and 18.95°C, respectively, and maximum relative humidity of 76.76%. In 2024-25, rainfall increased to 976.10 mm, with average maximum and minimum temperatures of 31.17°C and 18.89°C and maximum relative humidity of 81.14%.

RESULTS AND DISCUSSION

Pooled ANOVA showed significant genotypic effects ($P<0.05$) for all traits, indicating substantial genetic variability (Table 1). Replication effects were significant only for bulb polar and equatorial diameters, suggesting stable genotypic performance in both the seasons. Low error variances and coefficients of variation for most traits (e.g., 8.47% for plant height, 0.29% for thrips incidence) confirm the reliability of data. Genotypic performance for growth traits showed consistency across seasons. Bagdal Local had the highest pooled plant height (56.53 cm), followed by Bhima Safed (56.43 cm) and Bhima Raj (55.85 cm). Bhima Safed recorded the highest pooled number of leaves/plant (10.00), followed by W-364 GP, Bhima Shweta, Bhima Shubra and W-344 (9.75 each). Leaf area and LAI were highest in DOGR-1769 (498.21 cm^2, 3.32)

Corresponding author : kushal_1024@rediffmail.com
[2] University of Agricultural Sciences, Dharwad, Karnataka, India

Table 1: Pooled Analysis of variance for yield and yield attributing traits of onion genotypes

Source of variation/ parameter	Means			S.Em±	CD (5%)
	Replication	Genotypes	Error		
Degrees of freedom	**1**	**49**	**49**		
Plant height (cm)	449.86	40.58*	6.05	1.74	4.94
Number of leaves plant	0.04	0.87*	1.07	0.73	2.08
Leaf area (cm^2)	39315.75	4208.46*	417.31	14.44	41.05
Leaf area index	1.74	0.19*	0.02	0.10	0.27
Days to maturity (days)	28.09	12.43*	6.48	1.80	5.11
Pre-mature bolting (%)	5.29	2.18*	0.88	0.66	1.88
Bulb polar diameter (cm)	1182.67	23.11*	28.83	3.80	10.79
Bulb equatorial diameter (cm)	1028.29	23.63*	5.29	1.63	4.62
Bulb shape index	0.01	0.02*	0.00	0.04	0.11
Bulb neck thickness (cm)	0.02	0.05*	0.01	0.07	0.21
Number of rings per bulb	0.25	1.72*	0.55	0.52	1.48
Bulb dry matter content (g)	0.43	2.41*	0.40	0.45	1.27
Total soluble solid (^{0}B)	12.62	3.47*	0.20	0.31	0.89
Average weight of bulb (g)	8447.26	92.55*	65.74	5.73	16.29
Bulb yield per plot (kg)	0.20	0.39*	0.02	0.11	0.30
Bulb yield per hectare (t)	19.70	39.24*	2.25	1.06	3.01
Purple blotch incidence	65.61	0.76*	0.68	0.58	1.66
Thrips incidence	0.01	15.54*	0.00	0.01	0.03

* Significant at 5 % level of significance

Table 2: Mean performance of onion genotypes for bulb yield quality and pest incidence parameters

Genotype	Bulb dry matter			TSS			Avg. weight of bulb			Bulb yield (t/ ha)			Purple blotch (%)			Thrips		
	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled
Arka Bheem	14.21	13.39	13.80	13.10	13.75	13.43	74.80	63.43	69.12	33.94	33.37	33.66	2.00	3.50	2.75	4.47	4.45	4.46
Balichakra-W	15.57	15.83	15.70	16.05	15.34	15.70	75.55	57.65	66.60	34.50	32.77	33.64	2.00	2.00	2.00	6.01	5.98	6.00
Bagdal Local	15.13	15.37	15.25	11.75	13.34	12.55	72.30	55.18	63.74	42.58	37.54	40.06	1.50	2.50	2.00	5.04	5.02	5.03
Arka Kalyan	15.90	18.18	17.04	13.10	13.76	13.43	67.80	61.90	64.85	41.37	43.32	42.35	1.00	3.50	2.25	2.31	2.29	2.30
Balichakra-R	16.21	16.46	16.34	11.80	12.39	12.10	84.15	57.38	70.77	48.69	44.94	46.82	1.00	1.50	1.25	3.90	3.88	3.89
NHRDF Red	14.97	16.73	15.85	15.65	15.43	15.54	80.95	69.13	75.04	37.90	37.49	37.70	2.50	2.00	2.25	4.70	4.67	4.69
Telagi -L	15.25	15.49	15.37	11.70	12.81	12.26	81.70	75.35	78.53	39.14	39.33	39.24	2.00	1.50	1.75	3.68	3.65	3.67
Telagi -W	14.54	14.77	14.66	11.50	12.07	11.79	91.40	65.90	78.65	29.61	31.96	30.79	1.00	3.00	2.00	5.60	5.57	5.59
Bellary Red	15.23	15.47	15.35	12.50	13.13	12.82	73.80	60.38	67.09	43.23	41.70	42.47	1.50	2.00	1.75	1.59	1.59	1.59
GWO-1	15.94	16.19	16.07	12.35	12.97	12.66	76.00	66.85	71.43	43.70	41.36	42.53	1.00	3.50	2.25	4.35	4.34	4.35
GJRO-11	15.59	15.83	15.71	14.60	14.85	14.73	68.40	56.88	62.64	41.52	39.95	40.74	2.00	4.00	3.00	5.88	5.85	5.87
GJWO-3	15.13	15.37	15.25	14.85	15.59	15.22	80.75	64.20	72.48	32.31	33.71	33.01	1.00	3.50	2.25	4.33	4.30	4.32
Bhima Red	14.49	14.72	14.61	11.30	11.87	11.59	91.90	61.28	76.59	40.82	41.79	41.31	1.00	3.50	2.25	5.21	5.19	5.20
DOGR-1770	13.91	14.13	14.02	9.80	10.29	10.05	92.90	69.68	81.29	42.44	39.38	40.91	1.00	3.00	2.00	4.63	4.61	4.62
DOGR-1760	12.53	12.73	12.63	10.65	11.19	10.92	78.95	88.45	83.70	45.94	43.79	44.87	0.00	3.00	1.50	4.19	4.16	4.18
DOGR-1761	15.89	16.14	16.02	10.95	10.97	10.96	76.65	69.33	72.99	44.42	41.39	42.91	1.00	3.50	2.25	3.78	3.75	3.77
DOGR-1771	18.14	18.42	18.28	12.95	13.60	13.28	79.10	54.30	66.70	40.49	37.59	39.04	1.00	2.50	1.75	3.95	3.93	3.94
DOGR-1773	13.20	13.41	13.31	12.15	12.76	12.46	83.85	61.20	72.53	39.41	37.36	38.39	1.00	2.50	1.75	1.62	1.63	1.63
DOGR-1774	14.25	14.47	14.36	11.65	12.24	11.95	81.60	66.85	74.23	41.52	40.13	40.83	1.00	3.00	2.00	8.02	7.99	8.01
Bhima Super	13.89	14.11	14.00	12.90	13.54	13.22	82.05	76.90	79.48	43.05	40.15	41.60	1.00	4.00	2.50	2.09	2.08	2.09
Bhima Raj	15.05	15.28	15.17	10.35	10.87	10.61	85.40	69.33	77.37	45.42	46.42	45.92	1.00	3.50	2.25	2.07	2.07	2.07
Bhima Shakti	16.93	17.19	17.06	11.20	13.26	12.23	81.70	74.58	78.14	43.65	41.25	42.45	1.00	2.00	1.50	4.33	4.30	4.32
BhimaLightRed	14.51	14.74	14.63	12.05	12.65	12.35	74.60	57.18	65.89	39.05	40.07	39.56	1.00	1.00	1.00	1.98	1.97	1.98
DOGR-1772	13.25	13.46	13.36	13.10	13.76	13.43	75.55	60.43	67.99	39.81	41.83	40.82	0.50	2.50	1.50	1.92	1.91	1.92
DOGR-1769	15.09	15.33	15.21	10.60	11.13	10.87	77.20	65.45	71.33	45.21	41.00	43.11	1.00	1.00	1.00	8.39	8.35	8.37
DOGR-1768	14.39	14.61	14.50	10.50	11.03	10.77	83.45	78.10	80.78	34.04	33.38	33.71	0.50	2.00	1.25	11.00	10.93	10.97
BhimaDarkRed	15.73	15.97	15.85	9.50	12.98	11.24	84.95	68.98	76.97	34.46	35.13	34.80	0.00	1.00	0.50	6.42	6.40	6.41
Bhima Kiran	14.59	14.82	14.71	9.55	12.03	10.79	94.25	65.25	79.75	45.73	39.81	42.77	1.00	2.50	1.75	8.02	7.99	8.01
W-364 GP	14.55	14.78	14.67	11.80	12.39	12.10	96.60	71.18	83.89	36.53	40.29	38.41	0.00	3.50	1.75	6.28	6.26	6.27

Genotype	Bulb dry matter			TSS			Avg. weight of bulb			Bulb yield (t/ ha)			Purple blotch (%)			Thrips		
	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled	23-24	24-25	Pooled
BhimaShweta	14.47	14.20	14.34	12.75	14.39	13.57	79.30	54.60	66.95	40.26	38.78	39.52	0.00	3.00	1.50	4.01	3.99	4.00
W-405	17.59	15.86	16.73	11.10	11.65	11.38	80.55	58.80	69.68	31.99	30.94	31.47	0.00	3.50	1.75	11.85	11.78	11.82
Bhima Shubra	14.94	15.17	15.06	14.10	14.31	14.21	79.25	67.05	73.15	35.16	35.20	35.18	1.00	2.00	1.50	1.74	1.73	1.74
Bhima Safed	14.91	15.14	15.03	13.10	13.76	13.43	73.85	54.95	64.40	40.01	38.94	39.48	0.00	3.00	1.50	7.39	7.35	7.37
W-310-GP	16.80	16.59	16.70	11.70	12.29	12.00	82.95	66.00	74.48	33.09	34.73	33.91	1.00	2.50	1.75	3.06	3.09	3.08
W-344	15.11	15.35	15.23	10.75	11.79	11.27	93.95	62.28	78.12	42.99	41.17	42.08	0.00	2.50	1.25	3.33	3.32	3.33
W-355	16.51	16.27	16.39	11.75	12.34	12.05	96.85	77.83	87.34	40.52	41.03	40.78	0.00	3.00	1.50	0.90	0.91	0.91
W-361	17.09	15.36	16.23	13.40	14.07	13.74	88.00	68.73	78.37	40.96	37.74	39.35	0.00	2.50	1.25	2.01	2.01	2.01
W-504	16.01	14.76	15.39	13.65	14.33	13.99	95.85	53.20	74.53	33.20	33.69	33.45	0.50	2.50	1.50	8.99	8.94	8.97
W-448	16.03	16.28	16.16	12.15	12.76	12.46	92.50	58.75	75.63	44.95	40.06	42.51	0.00	3.00	1.50	6.35	6.32	6.34
W-125-GP	15.22	15.46	15.34	13.00	13.65	13.33	58.35	69.70	64.03	34.27	35.81	35.04	1.00	2.50	1.75	12.35	12.29	12.32
W-210-GP	15.41	15.67	15.54	12.90	13.54	13.22	95.80	59.18	77.49	33.15	34.12	33.64	0.50	3.00	1.75	8.45	8.41	8.43
W-203-GP	16.02	18.81	17.42	12.40	13.02	12.71	77.75	61.95	69.85	36.69	37.60	37.15	0.50	3.50	2.00	8.13	8.09	8.11
W-408	16.85	15.61	16.23	11.80	12.36	12.08	86.05	65.85	75.95	40.73	39.70	40.22	0.00	2.00	1.00	5.27	5.26	5.27
Furasangi	13.81	16.05	14.93	13.15	13.81	13.48	96.45	72.35	84.40	45.40	44.49	44.95	1.00	1.00	1.00	1.21	1.21	1.21
AFLR	15.65	14.39	15.02	12.50	13.13	12.82	83.90	64.85	74.38	46.33	44.51	45.42	0.50	1.00	0.75	7.70	7.66	7.68
NHRD Red-4	14.60	15.33	14.97	11.95	12.55	12.25	103.60	73.28	88.44	47.43	47.72	47.58	1.00	0.00	0.50	3.35	3.35	3.35
NHRDFRed-2	15.65	13.86	14.76	11.35	11.92	11.64	113.35	66.50	89.93	50.24	50.89	50.57	0.00	0.00	0.00	4.26	4.25	4.26
AFDR	13.25	13.97	13.61	10.80	11.34	11.07	96.80	61.23	79.02	40.96	38.93	39.95	0.00	2.00	1.00	5.19	5.15	5.17
Arakera local	14.94	15.17	15.06	11.15	11.71	11.43	66.10	64.63	65.37	34.43	36.64	35.54	0.00	0.50	0.25	0.51	0.51	0.51
N-53	16.25	15.00	15.63	14.45	14.66	14.56	81.70	57.70	69.70	37.72	35.68	36.70	1.00	1.00	1.00	6.54	6.48	6.51
S.Em±	0.90	0.96	0.45	0.86	0.93	0.31	7.76	5.55	5.73	3.38	2.80	1.06	0.26	0.51	0.58	0.47	0.44	0.01
CD (5%)	2.57	2.72	1.27	2.44	2.64	0.89	22.05	15.76	16.29	9.62	7.95	3.01	0.73	1.45	1.66	1.33	1.25	0.03
CV	8.40	8.80	4.15	9.96	10.18	3.52	13.15	12.06	10.92	11.96	10.11	3.79	45.78	29.93	51.59	13.33	12.61	0.29

and N-53 (497.42 cm^2, 3.32) in 2024-25, indicating strong photosynthetic capacity (Verma *et al.*, 2022). Days to maturity ranged from 87.50 days (DOGR-1774) to 100.00 days (Balichakra-W, Bhima Kiran, AFLR) in 2024-25. Bolting was lowest (0%) in NHRDF Red, GJWO-3 and DOGR-1769 in 2024-25, with a pooled minimum of 0% in W-310-GP and W-125-GP. These results align with those of Malik *et al.* (2024). The higher rainfall during 2024-25 (976.10 mm vs. 510.70 mm in 2023-24) likely influenced vegetative growth, reducing plant height in some genotypes (GJRO-11: 61.75 cm in 2023-24 to 50.45 cm in 2024-25).

Bulb traits exhibited significant variation. Telagi-W had highest pooled polar diameter (52.86 cm in 2024-25), while Bhima Shweta had the lowest (34.96 cm). W-504 showed the largest equatorial diameter (63.27 cm), and Balichakra-R and AFDR had highest shape index (1.04). Telagi-L exhibited thinnest neck (0.52 cm), ideal for storage (Gupta *et al.*, 2024). W-448 had the highest number of rings/bulb (11.50 pooled), DOGR-1771 the highest dry matter (18.42 g) and GJWO-3 the highest TSS (15.59 °Brix) in 2024-25 (Table 2.). Thin neck thickness and high TSS are critical for storage and processing (Saha *et al.*, 2024). The consistency of traits like neck thickness across seasons suggests genetic stability, as noted by Rani *et al.* (2024).

Bulb yield ranged from 30.94 tonnes/ha (W-405) to 50.89 tonnes/ha (NHRDF Red-2) in 2024-25. Other high yielding NHRDF Red-4 (47.72 tonnes/ha), Bhima Raj (46.42 tonnes/ha), and Balichakra-R (44.94 tonnes/ ha). DOGR-1760 recorded the highest bulb weight (88.45 g). Pooled yield data showed stable performance for top genotypes, despite higher rainfall during 2024-25, which may have enhanced bulb development in some genotypes (Choudhary *et al.*, 2022).

Pooled pest incidence data (Table 2) showed NHRDF Red-2 (0%) and Arakera local (0.25%) with the lowest purple blotch incidence and Arakera local (0.51) and W-355 (0.91) with the lowest thrips incidence. High thrips incidence was observed in W-125-GP (12.32 pooled) and DOGR-1768 (10.97). Low pest incidence in NHRDF lines aligns with findings of Chauhan *et al.* (2023), suggesting potential resistance.

CONCLUSION

The genotypes Telagi-L (thin neck), DOGR-1771 (high dry matter), and GJWO-3 (high TSS) are suitable for storage and processing. Low pest incidence in NHRDF Red-2 and Arakera local highlights their potential for integrated pest management. These genotypes are recommended for cultivation in Karnataka and similar agroclimatic zones, with potential for use in breeding programmes to enhance yield and quality.

REFERENCES

MA & FW, New Delhi, 2024, Horticultural Statistics at a Glance. Ministry of Agriculture, Govt. of India, New Delhi.

Best, K., 2000, Onion production and utilization: A global perspective. *Acta Horticulturae* **43**(1):15–22.

Chauhan, S. S. A., Islam, S., Prasad, L., Singh, S., Ellur, R. K. and Tomar, B. S, 2023. Screening of onion (*Allium cepa*) genotypes to find out novel resistant source against purple blotch (*Alternaria porri*). *Indian Journal of Agricultural Sciences* **93** (11): 1208–13.

Choudhary, M. L., Soni, R. L. and Kaushik, R. A. 2022. Evaluation of onion (*Allium cepa*) varieties for their suitability in tribal area of Dungarpur, Rajasthan. *Current. Horticulture.* **10** (2): 48–51.

Gupta, A. J., Benke, A., Gorrepati, K., Mahajan, V. and Singh, M. 2024. Trait association and variability study for biochemical and yield related traits in onion (*Allium cepa* L.). *Vegetable Science* **51** (1): 49–55.

Malik, G., Shah, R. A., Shabir, A., Dinkar, V., Mir, J. I. and Sharma, O. C. 2024. Evaluation of long-day onion (*Allium cepa* L.) genotypes for yield and quality traits under temperate conditions of Kashmir Valley in India. *Indian Journal of Plant Genetic Resources* **37** (2): 232–45.

Rani, K. S., Shree, S., Singh, V. K., Kumar, A. and Rajak, J. 2024. Studies on genetic variability and heritability in bulb onion (*Allium cepa* L.) in the South-Eastern plains of Bihar, India. *Ecology Environment and Conservation* **30**: 5109–13.

Saha, P., Sharangi, A. B., Sengupta, S., Thapa, U., Singh, A. P., Chatterjee, S. and Chattopadhyay, A., 2024, Breeding potential of red- and white-skinned onion (*Allium cepa* L.) genotypes for economic traits using multivariate analysis. *International Journal of Vegetable Science* **31** (1): 5–23.

Thamburaj, S. and Singh, N., 2019, *Textbook of Vegetable Crops*. Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, pp. 210–225.

Verma, A. K., Singh, P. P., Singh, D., Saroj, P. L. and Singh, M., 2022, Performance evaluation and scope of onion improvement under hot arid conditions. *Indian Journal of Horticulture* **79** (2): 202–07.

Current Horticulture **14**(2): 117-120, April–June 2026
DOI: 10.5958/2455-7560.2026.00031.5
Received: 9 June 2025; Accepted: 19 June 2026

Integrated nutrient management in coriander (*Coriandrum sativum*)

J. M. Thumar, P. P. Bhalerao* and B. M. Tandel

ASPEE College of Horticulture, NAU, Navsari, Gujarat, India

Abstract

The field study was carried out to study the integrated nutrient management in coriander (Coriandrum sativum L.) var. GCo-3" during *rabi*, 2023-24 at Regional Horticultural Research Station, ASPEE College of Horticulture, NAU, Navsari, Gujarat, India. The experiment was conducted in randomized block design with ten treatments and three replications consisting of *viz.* T_1: FYM 10 t/ha and 100 % RDF (60:30:00 kg NPK/ha), T_2: FYM 5 t/ha + 75 % RDF, T_3: FYM 10 t/ha + 50 % RDF, T_4: vermicompost 2 t/ha + 75 % RDF, T_5: vermicompost 4 t/ha + 50 % RDF, T_6: biocompost 2 t/ha + 75 % RDF, T_7: biocompost 4 t/ha + 50 % RDF, T_8: FYM 5 t/ha + 50 % RDF +1 % novel organic liquid nutrients T_9: vermicompost 2 t/ha + 50 % RDF + 1 % novel organic liquid nutrients and T_{10}: biocompost 2 t/ha + 50 % RDF + 1 % novel organic liquid nutrients. The application of FYM 5 t/ha + 50 % RDF + 1 % novel organic liquid nutrients (T_8) gave maximum plant height (24.17 cm, 60.71 cm, 112.15 cm and 116.29 cm), highest number of primary branches/plant (1.90, 2.67, 4.07 and 4.27), total number of branches/plant (7.60, 9.53, 11.80 and 15.40), petiole length (21.18 cm, 18.68 cm, 13.50 cm and 8.48 cm) and leaf length (3.52 cm, 3.67 cm, 3.77 cm and 3.85 cm) 30, 60, 90 days and at harvest after sowing, respectively. Maximum number of umbels/plant (17.47), number of umbellates/umbel (5.87), number of seeds/umbellates (7.93), highest seed weight/plant (5.94 g), test weight of (000 seed weight) (14.33 g), seed yield (2002.93 kg/ha) and straw yield (2541.67 kg/ha) as well as oil yield (14.21 kg/ha) were observed under application of FYM 5 t/ha + 50 % RDF + 1 % novel organic liquid nutrients (T_8). The highest benefit:cost ratio (1.79) and maximum net realization (1,35,062 ₹/ha) were obtained under FYM 5 t/ha + 50 % RDF + 1 % novel organic liquid nutrients (T_8). Whereas, application of FYM 10 t/ha + 50 % RDF (T_3) improved soil nutrient status.

Key words: Nutrient, Growth, Yield, Quality, Integrated nutrient management

Coriander (*Coriandrum sativum* L.) is an annual herbaceous plant. India is the top producer of coriander in reference to an area of 5.53 lakh ha and a production of 7.35 lakh MT with an average yield of 1.32 MT ha^{-1}. In Gujarat, 1.88 lakh MT of coriander was produced in an area of 1.25 lakh ha. Organic forms of nutrients such as FYM, vermicompost and biocompost, constitute a potential renewable source of nutrient supply to crops under all situations, as well as improving the physical condition of soil to replenish and maintain its humus status in order to continue the optimum condition for soil microorganisms activities (Gruhn *et al.*, 2000). Integrated nutrient management (INM) is the process of maintaining or adjusting soil fertility and supply of plant nutrients to an ideal level of growth, development and intended yield by optimizing the benefits from all possible sources of plant nutrients through the appropriate combination of chemical fertilizers and organic manures (Gadipe *et al.,* 2020). Novel organic liquid nutrients which was prepared from the sap of banana pseudostem which is contains enough essential nutrient and plant growth hormone for growth and development of crops (Desai *et al.,* 2016). Although a good deal of information is available on fertilizer application for higher production of coriander and so far FYM is the organic source which has been used predominantly but meagre work has been done on vermicompost, bio compost and NOVEL as an organic source as far as coriander. Therefore, an experiment was conducted on integrated nutrient management in coriander.

Corresponding author : pankaj5bhalerao@nau.in

MATERIALS AND METHODS

An field study was carried out, to study the "integrated nutrient management in coriander var. GCo-3" during *rabi*, 2023-24 at Regional Horticultural Research Station, ASPEE College of Horticulture, NAU, Navsari, Gujarat, India. The experiment was conducted in randomized block design with ten treatments and three replications consisting of *viz.* T_1: FYM 10 t/ha and 100 % RDF (60:30:00 kg NPK/ha), T_2: FYM 5 t/ha + 75 % RDF, T_3: FYM 10 t/ha + 50 % RDF, T_4: vermicompost 2 t/ha + 75 % RDF, T_5: vermicompost 4 t/ha + 50 % RDF, T_6: bio-compost 2 t/ha + 75 % RDF, T_7: bio-compost 4 t/ha + 50 % RDF, T_8: FYM 5 t/ha + 50 % RDF +1 % novel organic liquid nutrients T_9: vermicompost 2 t/ha + 50 % RDF + 1 % novel organic liquid nutrients and T_{10}: bio-compost 2 t/ha + 50 % RDF + 1 % novel organic liquid nutrients. Organics (FYM, vermicompost and bio-compost) were applied at the time of sowing whereas, inorganics (N-urea and P-SSP), i.e. nitrogen were applied in two equal splits mainly, half quantity of nitrogen with full dose of phosphorus were applied at basal and remaining half quantity of nitrogen applied as top dressed at 30 DAS.

Table 1: Effect of integrated nutrient management on growth attributes of coriander cv. GCo 3

Treatment	Plant height (cm)				Number of primary branches/plant				Total number of branches/plant				Petiole length (cm)				Leaf length (cm)			
	30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest
T_1	23.00	53.19	100.55	105.01	1.80	2.20	3.53	3.67	6.67	9.00	10.20	13.60	19.51	17.27	10.95	6.65	3.05	3.13	3.25	3.36
T_2	22.13	52.13	99.53	103.82	1.53	2.00	3.00	3.53	6.27	8.40	10.07	11.07	17.79	14.95	10.52	6.52	2.80	2.91	3.04	3.32
T_3	23.41	60.12	111.97	115.56	1.87	2.60	3.60	3.87	7.13	9.20	11.73	15.27	20.69	18.28	13.44	8.36	3.43	3.63	3.73	3.81
T_4	20.82	51.79	98.82	101.95	1.37	1.73	2.43	2.87	5.60	7.73	9.40	10.60	16.31	13.69	9.56	6.11	2.60	2.73	2.90	3.21
T_5	21.13	52.01	98.87	102.84	1.50	1.87	2.60	3.07	6.00	8.07	10.00	10.73	17.10	14.26	9.91	6.14	2.71	2.79	2.99	3.25
T_6	23.32	59.02	111.53	114.30	1.83	2.27	3.60	3.80	6.88	9.13	11.60	14.33	20.31	17.79	12.40	7.82	3.42	3.61	3.72	3.80
T_7	22.12	52.11	99.31	102.16	1.53	1.97	2.87	3.27	6.07	8.27	9.87	10.87	17.27	14.63	10.21	6.39	2.79	2.88	2.99	3.29
T_8	24.17	60.71	112.15	116.29	1.90	2.67	4.07	4.27	7.60	9.53	11.80	15.40	21.18	18.68	13.50	8.48	3.52	3.67	3.77	3.85
T_9	22.61	53.07	99.71	104.04	1.57	2.07	3.13	3.57	6.33	8.47	10.13	11.27	18.28	15.35	10.69	6.63	2.90	2.92	3.08	3.32
T_{10}	22.83	53.14	100.13	104.56	1.57	2.20	3.20	3.60	6.60	8.53	10.13	11.40	19.27	15.44	10.71	6.64	2.92	2.99	3.11	3.35
S.Em. (±)	0.68	2.32	3.79	3.71	0.10	0.13	0.19	0.21	0.30	0.31	0.51	0.64	0.83	1.04	0.72	0.42	0.18	0.18	0.17	0.15
CD (5 %)	NS	6.93	11.36	11.09	0.30	0.40	0.55	0.64	0.89	0.91	1.54	1.91	2.50	3.12	2.17	1.27	0.55	0.53	0.50	0.45
CV (%)	5.20	7.33	6.36	6.00	10.54	10.79	10.07	10.45	7.93	6.14	8.48	8.90	7.70	11.27	11.21	10.50	10.60	9.83	8.89	7.56

Table 2: Effect of integrated nutrient management on yield, quality and soil nutrient status of coriander cv. GCo 3

Treatment	Yield-attributing characters							Quality contents		Soil nutrient status		
	Number of umbels/ plant	Number of umbellates/ umbel	Number of seeds/ umbellates	Seed weight/ plant (g)	Test weight (000 seed weight in g)	Seed yield (kg/ha)	Straw yield (kg/ha)	Oil content in seed (%)	Oil yield (kg/ha)	Organic carbon (%)	Nitrogen (kg/ha)	Phosphorus (kg/ha)
T_1	15.07	4.73	6.73	4.91	13.00	1711.17	2243.47	0.68	11.59	0.84	309.33	43.36
T_2	14.53	4.60	6.53	4.82	12.67	1606.14	2166.34	0.66	10.54	0.77	298.54	47.59
T_3	17.40	5.60	7.67	5.92	13.83	1919.16	2459.38	0.69	13.27	0.88	335.38	52.61
T_4	13.87	4.40	6.40	4.54	12.17	1515.64	1976.85	0.65	9.92	0.76	299.27	50.38
T_5	14.20	4.53	6.47	4.68	12.33	1562.32	2003.47	0.65	10.10	0.80	322.44	50.13
T_6	17.33	5.47	7.53	5.74	13.33	1813.76	2297.45	0.69	12.57	0.83	325.64	49.33
T_7	14.33	4.53	6.47	4.78	12.50	1579.81	2062.50	0.66	10.37	0.84	306.45	47.28
T_8	17.47	5.87	7.93	5.94	14.33	2002.93	2541.67	0.71	14.21	0.87	330.82	52.44
T_9	14.80	4.67	6.53	4.86	12.67	1681.39	2225.69	0.67	11.32	0.80	295.02	51.50
T_{10}	14.93	4.67	6.60	4.88	13.00	1683.56	2186.34	0.67	11.20	0.84	309.66	49.19
S.Em. (±)	0.81	0.31	0.36	0.29	0.38	84.48	100.11	0.02	0.63	0.02	8.97	1.65
CD (5 %)	2.39	0.91	1.08	0.86	1.12	250.98	297.41	NS	1.88	0.06	26.64	4.92
CV (%)	9.06	10.80	9.14	9.80	5.02	8.57	7.82	5.34	9.52	4.65	4.96	5.80

Table 3: Effect of integrated nutrient management on economics of coriander

Treatment	Seed yield (kg/ha)	Treatment cost (Rs. ha^{-1})	Fixed cost (₹/ha)	Total cost (₹/ha)	Gross income (₹/ha)	Net income (₹/ha)	BCR
T_1	1711.17	65,144	11,678.74	76,823.19	1,79,672.85	1,02,849.66	1.34
T_2	1606.14	61,412	10,961.91	72,374.36	1,68,644.70	96,270.34	1.33
T_3	1919.16	63,680	13,098.27	76,778.72	2,01,511.80	1,24,733.08	1.62
T_4	1515.64	74,412	8,866.52	83,278.97	1,59,142.20	75,863.23	0.91
T_5	1562.32	89,680	9,139.56	98,820.01	1,64,043.60	65,223.59	0.66
T_6	1813.76	59,612	10,610.47	70,222.92	1,90,444.80	1,20,221.88	1.71
T_7	1579.81	60,080	92,41.89	69,322.34	1,65,880.05	96,557.71	1.39
T_8	2002.93	63,528	11,717.16	75,245.61	2,10,307.65	1,35,062.04	1.79
T_9	1681.39	76,528	9,836.12	86,364.57	1,76,545.95	90,181.38	1.04
T_{10}	1683.56	61,728	9,848.80	71,577.25	1,76,773.80	1,05,196.55	1.47

Note: Selling price of coriander seeds Rs.105/kg.

The foliar application of novel organic liquid nutrients was done at 25 and 50 days after sowing. The soil of the experimental plot was clay in texture with pH values for 15-30 cm depths is 7.75. The experimental field were prepared by one deep ploughing followed by one harrowing. Flat beds of 2.4 m x 2.4 m size were prepared and seed of coriander variety GCo. 3 was sown at 20 cm × 10 cm spacing during last week of November, 2023. The cultural practices and nutrient management (FYM @ 10 t ha^{-1} with RDF @ 20:10:00 NPK kg/ha) were carried out as par the recommendations. Observations on different growth parameters was recorded 30 and 50 days after sowing from five randomly selected plants from each plots whereas, yield attributing characters were recorded at the time of harvesting. The quality parameters, *viz.* essential oil content was determined by using Clevenger type apparatus and the yield of essential oil was computed by formula. The chemical properties of the soil from the depth of 15-30 cm. were determined before and after the experiment by Jackson (1973) methods.

RESULTS AND DISCUSSION

The data revealed that, application of FYM 5 t/ha + 50 % RDF + 1 % novel organic liquid nutrients (T_8) significantly recorded maximum plant height (60.71 cm, 112.15 cm and 116.29 cm), highest number of primary branches/plant (1.90, 2.67, 4.07 and 4.27), total number of branches/plant (7.60, 9.53, 11.80 and 15.40), petiole length (21.18 cm, 18.68 cm, 13.50 cm and 8.48 cm) and leaf length (3.52 cm, 3.67 cm, 3.77 cm and 3.85 cm) 30, 60, 90 days and at harvest after sowing, respectively. FYM 5 t/ha + 50 % RDF + 1 % novel organic liquid nutrients (T_8) showed significant results among the treatment that might be due to high efficiency of INM combination (Sunanda *et al.*, 2014 and Kumari *et al.*, 2020). The novel organic liquid nutrients enhanced cell division and cell elongation (Suvarna, 2024; Manasa Bhat *et al.*, 2022 and Parikh *et al.*, 2023) and its combination with FYM, a narrow C:N ratio may produce more humic acid and humic substances, improving aeration and favouring beneficial microbial activity (Kumar *et al.*, 2016 and Manasa Bhat *et al.*, 2022).

The FYM 5 t/ha + 50 % RDF + 1 % novel organic liquid nutrients (T_8) gave maximum number of umbels/plant (17.47), number of umbellates/umbel (5.87), number of seeds/umbellates (7.93), highest seed weight/plant (5.94g), test weight of (000 seed) (14.33 g), seed yield (2002.93 kg/ha) and straw yield (2541.67 kg/ha). The higher values of yield might be due to be the effect of a perfect combination of integrated nutrients (FYM 5 t/ha + 50 % RDF + 1 % novel organic liquid nutrients), which contributed to the increased growth of plants in respect to the height of the plant and the number of leaves. The healthy plant growth and good soil conditions directly reflect on higher rate of photosynthesis, metabolites and nutrient uptake; thus, increased carbohydrate accumulation (Dhwani Bartwal *et al.*, 2022). The influence of novel organic liquid nutrients in yield attributes might be due to presence of a lavish amount of macro and micronutrients. The nutrients N and K at higher rate exerted a significant positive influence on yield. The enhancement of yield could have been further facilitated by optimizing the synthesis of carbohydrates and their efficient translocation to the potential storage organs through better growth and more number of branches per plant.

Essential oil content (%) recorded were failed to express their significant differences among the different treatments, but oil yield showed significantly higher (14.21 kg/ha) in FYM 5 t/ha + 50% RDF + 1% novel organic liquid nutrients (T_8). The higher oil yield with these treatments is attributed mainly to higher values of oil content and seed yields. Moreover, novel organic liquid nutrients increased the cation exchange capacity of roots and make them potent in absorbing other nutrient ions like H_2PO_4, K, *etc.* (Parikh *et al.,* 2023).

The treatments combination of FYM 5 t/ha + 50% RDF + 1% novel organic liquid nutrients (T_8) registered the highest net profit 1,35,062 ₹/ha with B:CR value of 1.79 as compared to rest of the treatments. This might be due to higher yield and lower investment in this treatment which in turns lead to maximum net profit as compared to other treatments. Similar results were obtained by Parikh *et al.* (2023) in turmeric.

The significantly higher organic carbon content (0.88%) in soil was recorded with application of FYM 10 t/ha + 50% RDF (T_3). The available N content (335.38 kg/ha) and P_2O_5 content (52.61 kg/ha) in soil was recorded significantly higher with the same treatment, i.e. FYM 10 t/ha + 50% RDF (T_3).

The complex organic cations chelate Al^{+3}, Fe^{+3} and Ca^{+3} and thus decrease the phosphate precipitating power of these cations and thereby increased in phosphorus availability with organic manure in higher quantity attributed to mineralization of organic phosphorus and production of organic acid making soil phosphorus more available (Dhwani Bartwal *et al.,* 2022 and Donga, 2014). Similar results were observed by Manasa Bhat *et al.* (2022) and reported FYM with inorganic fertilizer affect soil nutrient status in turmeric crop. This might be due to gradual and steady release of nutrient during the growth period as well as enhanced biological activity and proper nutrition to the crop.

REFERENCES

Desai CS, Patel JM, Pawar SL, Usadadia VP, Naik VR and Savani NG. 2016. 'Value added products from banana pseudostem.' Research Scientist, Soil and Water Management Research Unit, NAU, Navsari, pp. 55-56.

Dhwani Bartwal, Dudhat MS, Patel RS and Rathod AM. 2022. 'Effect of integrated nutrient management on growth, yield and economics of coriander (*Coriandrum sativum* L.)' *Ph.D. (Agri.) Thesis,* Navsari Agricultural University, Navsari, Gujarat.

Donga SJ. 2014. 'Effect of organic manures and bio fertilizers on growth, yield and economics of coriander'. M.Sc. (Agri.) Thesis, Junagadh Agricultural University, Junagadh, Gujarat.

Gadipe V., Rajitha G, Shashikanth M, Reddy KKK, Kumar AE and Jhonson S. 2020. 'Integrated nutrient management (INM): Meaning, Principles, Goals and Components' **1**(6): 32-35.

Gruhn P., Goletti F. and Yudelman M. 2000. Integrated nutrient management, soil fertility, and sustainable agriculture: current issues and future challenges. *International Food Policy Research Institute,* p.15.

Jackson ML. 1973. "Soil Chemical Analysis". Prentice - Hall of India (Pvt.) Ltd., New Delhi, India, 415 p.

Kumar KR, Narasimha SR and Kumar NR. 2016. Effect of organic and inorganic nutrient sources on growth, quality and yield of turmeric (*Curcuma longa* L.). *Green Farming* **7**(4): 889-92.

Kumari KU, Jyothi KU, Reddy RVSK, Sujatha RV, Rajendra K, Prasad CP and Sekhar V. 2020. Optimization of yield, quality and nutrient uptake of chilli (*Capsicum annuum* L.) through intercropping and integrated nutrient management practices. *Journal of Pharmaceutical Innovation* **9** (9): 260-63.

Manasa Bhat, Bhalerao PP and Tandel BM. 2023. Integrated nutrient management in turmeric (*Curcuma longa* L.) cv. GNT-2. *Journal of Plantation Crops* **51** (3): 101-107.

Parikh RP, Bhalerao PP and Patil SJ. 2023. Effect of foliar application of organic liquid sources on growth, yield and quality of turmeric cv. GNT-2. *Current Horticulture* **11** (1): 30–32.

Sunanda BB, Shetty GR and Venkatesh J. 2014. Influence of integrated nutrient management on growth, yield and quality of Kasuri Methi (*Trigonella corniculata* L.) under hill zone of Karnataka. *International Journal of Seed Spices* **4** (2):62-67.

Suvarna. 2023. 'Effect of foliar application of organics on growth and yield of coriander'. *M. Sc. (Horti.) Thesis,* Navsari Agricultural University, Navsari, Gujarat.

Continued from 2nd Cover

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
- Abstracting Agencies of the International and National repute

Disclaimer

• All disputes are subject to the exclusive jurisdiction of competent courts and forums in Ghaziabad only • The society does not assume any responsibility for opinions offered by the authors in the articles and no material in any form can be reproduced without permission of the society • The society is not responsible for any delay in delivery of the journal to the subscribers due to unforeseen circumstances or postal delay • Readers are recommended to make appropriate enquiries before sending money, incurring expenses or entering into commitments in relation to any advertisement appearing in this journal • The society does not vouch for any claim made by the advertisers of products and services • The publisher and the editors of the publication shall not be held liable for any consequences in the event of such claims not being honoured by the advertisers.

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