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Review Article

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Medicinal Coleus (*Coleus forskohlii* Briq): Different Methods of Propagation – A Review

Sanjaai Kumar ¹, Santhos Raj ¹, Jones Ponraj ² ✉¹ Department of Horticulture, Tamil Nadu Agricultural University, Coimbatore, 641003, Tamil Nadu, India² Assistant Professor, Department of Horticulture, Tamil Nadu Agricultural University, Coimbatore, 641003, Tamil Nadu, India✉ Corresponding author: kriswinjones@gmail.comInternational Journal of Horticulture, 2026, Vol.16, No.3 doi: [10.5376/ijh.2026.16.0012](https://doi.org/10.5376/ijh.2026.16.0012)

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Abstract *Coleus forskohlii* (Briq.), a prominent member of the Lamiaceae family, is a highly valued medicinal herb in Indian Ayurvedic medicine and the global pharmaceutical industry. Its primary therapeutic significance is attributed to forskolin, a unique labdane diterpene concentrated in the root tubers. Forskolin serves as a potent adenylate cyclase activator, making it indispensable for treating ailments such as hypertension, glaucoma, and congestive heart failure. However, the commercial cultivation of *C. forskohlii* faces significant challenges; conventional propagation via vegetative cuttings is often hindered by slow multiplication rates, seasonal limitations, and susceptibility to soil-borne pathogens. This review provides a comprehensive analysis of various propagation methodologies and biotechnological advancements aimed at enhancing biomass and forskolin yield. It evaluates the impact of plant density, cutting types, and planting methods on root productivity. A significant focus is placed on in vitro techniques, including shoot induction and callus formation using Murashige and Skoog (MS) media supplemented with specific growth regulators like BAP, NAA, and 2,4-D. Furthermore, the review explores the efficacy of brassinosteroids in promoting root development and the application of somatic embryogenesis and direct organogenesis for rapid, large-scale clonal propagation. These biotechnological approaches not only ensure the production of genetically uniform, disease-free planting material but also offer sustainable strategies for the conservation of this endangered medicinal species. By integrating tissue culture with elicitation strategies, the industry can better meet the rising global demand for forskolin while preserving natural germplasm.

Keywords Medicinal coleus (*Coleus forskohlii* Briq); Lamiaceae family; Direct organogenesis; Somatic embryogenesis; Brassinosteroid; Leaf explants; Stem cuttings; Forskolin

1 Introduction

Coleus forskohlii belongs to the family Lamiaceae is an important plant in Indian Ayurvedic medicine and herbaceous plant that usually grows at a height of 600–1,500 ft and is spread over the subtropical warm temperate climatic zones of India. It is an ancient and important root drug claimed to improve appetite, increase vitality and useful by curing the ailments like inflammation, flatulence, dropsy etc. (Rupp et al., 1986). It occurs in sub-tropical Himalayan regions from Kumaon to Nepal, Bihar and Deccan plateau of southern India. It is widely cultivated in Rajasthan, Maharashtra, Gujarat, Karnataka, Tamil Nadu and Andhra Pradesh and its present annual production is about 100 tons from the area of 700 ha in India, cultivation of *C. forskohlii* is picking up in recent years. It is a fast-growing herb and hence more amenable to get exposed to variety of environmental stress.

It is Commercially propagated by the means of vegetative cuttings (Reddy et al., 2001). Conventional means of propagation through vegetative cuttings is not suitable to meet the increasing demand of this species due to limited number of propagules produced in each cycle. In vitro propagation is the most efficient and reliable technique for production of ample planting stock of genetic uniformity. Its rapid mode of vegetative propagation makes it a suitable candidate for micro propagation (Biondi and Thorpe, 1982).

It is highly valuable as a medicinal plant due to a biologically active compound labdane diterpene present in the root tubers called 'forskolin' (Bhat et al., 1977). An active diterpenoid in roots, it poses multiple biological activities such as positive inotropic, anti-hypertensive and antiglaucoma (Seamon and Daly, 1981), which is

widely used by pharmaceutical industry due to its wide range of therapeutic effects. The main feature of forskolin is in its roots having unique mechanism of generating cyclic adenosine monophosphate in the cells through direct activation of the catalytic unit of adenylate cyclase enzyme (Yanagihara et al., 1996). For commercial cultivation of this crop optimization of plant population per unit area, method of planting and type of cutting are the prime factors in terms of root yield of medicinal coleus.

The most important problem to the commercial growers of coleus is optimum plant density, appropriate type of cutting, method of planting and selecting suitable cultivar. The species is known well for its pharmacological importance.

2 Botanical and Phytochemical Background

2.1 Taxonomical classification

The plant belongs to the family Lamiaceae and the order Lamiales. Commonly known as the mint family, it includes a number of potent medicinal plants. It consists of 236 genera and 7,000 species, it is the largest family of the order Lamia. The genus *Coleus* was first described in 1790, with *C. forskohlii* classified under the family Lamiaceae, highlighting its botanical significance. This classification underscores the plant's historical use in traditional medicine and its potential for further research in phytochemistry.

2.2 Phytochemistry and medicinal relevance

A Biologically active compound labdane diterpene present in the root tubers called 'forskolin' a key compound extracted from the roots, activates adenylate cyclase, leading to increased levels of cyclic adenosine monophosphate (cAMP) in the cells (Seamon and Daly, 1981). These cAMP plays a key role in various body functions, including heart muscle contraction, smooth muscle relaxation, insulin secretion, and thyroid function and has various physiological effects (Kavitha et al., 2010). The study identifies several minor diterpenoids and other phytochemicals present in *C. forskohlii*, emphasizing the complexity and potential of its chemical profile.

3 Conventional Propagation Methods

3.1 Rooted cuttings with different planting methods and varieties

The yield of medicinal coleus is influenced by plant density, cutting type, and planting methods (Chandrasekhar et al., 2016). Chintapalli local and K-8 varieties were planted using ridge and furrow and flatbed methods, with ridge and furrow methods yielding the highest dry root yield. Genetic factors also significantly impact root yield performance.

3.2 Role of leaves and cutting type in rooting

The physiological status of the cutting is vital for successful rooting. Semi-hardwood stem cuttings that retain apical leaves show significantly higher rooting percentages and quality (Belniaki et al., 2018). Studies found that cuttings with leaves produced an average of 16 roots, compared to only 5.7 roots in leafless cuttings, suggesting that endogenous auxins or carbohydrates from the leaves facilitate better establishment.

3.3 Ex situ propagation through stem cuttings

The methodology involved selecting disease-free, mature stem cuttings from the mother plant are grown in prepared beds and poly bags in a combination of sand, soil, and manure was used to create optimal growing conditions for the stem cuttings (Patel, 2016). A well-structured water and drainage system is crucial for the successful growth of *Coleus forskohlii*, preventing water logging and plant damage. Results indicated that the mixed media in poly bags facilitated rapid root and shoot development, supporting the plant's propagation and contributing to its ex-situ conservation efforts.

4 In vitro Regeneration and Micropropagation

4.1 In vitro shoot induction using MS medium

Leaf explants were collected and subjected to thorough surface sterilization using running water, antifungal agents, and detergents to ensure aseptic conditions (Murashige and Skoog, 1962). After sterilization, explants were cut into smaller pieces and inoculated in MS media with varying concentrations of hormones 2,4-D (0, 0.01, 0.02,

0.03, 0.04, 0.1, 0.5, 0.1, 0.2, 2.5 mg/L), BAP (0.0, 0.01, 0.02, 0.03, 0.04, 0.1, 0.5, 0.1, 1.5 mg/L) in different concentration and combination to promote callus formation. The pH of the culture media was maintained between 5.4-5.7, adjusted with NaOH or HCl, and solidified with 0.8% agar.

Cultures were kept at a controlled temperature of (22±2) °C with a 16-hour photoperiod, with sub culturing performed every two weeks. Callus induction involved sub culturing leaf explants in different concentrations of BAP and NAA to enhance the shoot formation. In regular intervals of two weeks were maintained for monitoring and promoting the number of shoots generated from the callus (Dodds and Roberts, 1982). The study found that MS medium supplemented with BAP and 2,4-D was more effective for callus induction compared to NAA and BAP. Callus exhibited a range of colours (Lisowska and Wysokinska, 2000) and showed significant genetic variability, leading to successful multiple shoot formation from the leaf explants.

4.2 Effective propagation method for salt tolerance

Using apical tip as meristem as explant it resulted in quicker plant growth than Nodal Segment. This Medicinal coleus explant grown in the NaCl Medium of different Concentration from 0.1% to 0.4%. Later they found that the explant of medicinal coleus was able to withstand and grow at the low concentration of 0.2% of NaCl with the support of BAP and NAA (Sharan et al., 2014).

Generally, the use of BAP is considered to be most suitable for promoting large-scale multiplication and micropropagation of various plant species (Shrivastava and Banerjee, 2008). In *C. forskohlii*, BAP alone has shown best result in promoting multiple shoots formation from the nodal segments and shoot tips (Sen and Sharma, 1991).

4.3 Effect of brassinosteroid in rooting

Swamy et al. (2021) found that the application of brassinosteroid significantly increased root numbers in medicinal coleus plants. The application of 28-homobrassinolide at 100 µM resulted in an 85% increase in root numbers by day 15, indicating its effectiveness in promoting rooting. The findings suggest that brassinosteroid could be pivotal in commercial cultivation practices for medicinal plants, enhancing both rooting and vegetative growth (Rao et al., 2010). Terminal cuttings from healthy coleus plants were treated with BRs, monitored for 160 days, and found to increase carbohydrate levels and forskolin content in roots, suggesting a link between growth regulators and secondary metabolite production.

4.4 Effect of cytokinin combined elicitors in coleus

In vitro culture techniques using cytokinins combined with elicitors can enhance both the propagation efficiency and secondary metabolite production of *Coleus* spp., a plant group with notable medicinal value. Cytokinins promote cell division, shoot differentiation, and tissue proliferation, while elicitors stimulate defense-related physiological responses and activate secondary metabolic pathways. Their combined application may therefore improve the accumulation of bioactive compounds associated with antioxidant, anti-inflammatory, and pharmacological activities.

Compared with conventional cultivation, tissue culture provides controlled growth conditions, stable nutrient availability, and a shorter production cycle. These factors create a favorable environment for secondary metabolite biosynthesis in *Coleus* spp. Previous studies have shown that controlled culture conditions and nutrient supply can increase secondary metabolite levels in tissue-cultured plants (Govindaraju et al., 2018). Therefore, optimizing cytokinin types and elicitor combinations is an effective strategy for improving both in vitro propagation and medicinal compound production in coleus.

4.5 Shoot regeneration from proximal, middle and distal segment of *Coleus forskohlii* leaf explants

Rapid shoot regeneration was examined in Three different segments of coleus leaf explant (Proximal, Middle and Distal) where cultured on Murashige and Skoog (MS) Medium with different concentrations of BAP, KIN, NAA, and IAA were tested for shoot elongation. Although callus proliferation was observed, KIN was found to be ineffective in the present study. However, Sharma et al. (1991) previously reported that KIN-enriched media

increased the frequency of callus formation from leaf explants. BAP with different concentrations (0.5, 1.0, 2.5, 5.0) in which BAP at 5.0 mg/L yielded the highest shoot regeneration rate is found to be effective for micropropagation of *C. forskohlii* then Distal leaf segments showed superior regeneration compared to proximal and middle segments, likely due to the presence of more meristematic tissues in the proximal area (Krishna et al., 2010).

4.6 Shoot organogenesis

Focuses on the development of callus from *C. forskohlii* leaf segments in a sterile environment under controlled conditions. The results show that cytokinin and auxin plays a crucial role in shoot differentiation. Kinetin, when combined with NAA or IAA, leads to the highest shoot regeneration frequency. The study also found that rooting efficiency is highest in half-strength MS medium without growth regulators. The study confirms that in vitro-produced plants maintain clonal purity and forskolin content, making it viable for commercial propagation (Sairam Reddy et al., 2001).

4.7 Large scale clonal propagation

Large scale clonal propagation leaf lamina is used as an explant and it is achieved in the media containing 2 μ M BA + 0.1 μ M NAA Where a highest number of 35 shoots/explant were produced. Later they transferred to root induction medium comprising of IBA, NAA and IAA (1-5 μ M) in half-strength MS medium to determine the Most suitable shoot length for proper root induction. The rooted plantlets were acclimatized in field conditions after proper hardening (Sahai and Shahzad, 2010).

4.8 Roots cultivated in shake flask

Forskolin production from *C. forskohlii* roots can be achieved through various cultivation methods, including shake flasks and bioreactors. The transformed hairy root cultures, initiated via *Agrobacterium rhizogenes*, can produce forskolin in significant quantities, with optimal conditions yielding up to 14 mg/L after 21 days. Hormone-free media and sucrose additions enhance growth and forskolin production, with specific elicitors like methyl jasmonic acid boosting yields. Cutting roots without negatively impacting growth or productivity is a notable advantage in scaling up production (Krombholz et al., 1992).

4.9 Somatic embryogenesis

In vitro plant regeneration through somatic embryogenesis in *Coleus forskohlii* Briq. has been successfully established using leaf explants (Gopi and Mary, 2014). Research indicates that the combination of plant growth regulators (PGRs) significantly influences the regeneration process (Yasmin et al., 2001).

Specifically, a medium containing 2,4-dichlorophenoxyacetic acid (2,4-D) and 6-benzylaminopurine (BAP) yielded the highest frequency of direct somatic embryogenesis, achieving up to 80% success in embryo maturation and conversion to plantlets. Additionally, alternative methods utilizing direct organogenesis from leaf explants have shown promise, with protocols achieving up to 35 shoots per explant using optimized concentrations of BAP and auxins (Dode et al., 2003).

These findings highlight the potential for both somatic embryogenesis and direct organogenesis as effective strategies for the mass propagation and conservation of this medicinally important species, although the reliance on specific PGR combinations may limit broader applicability.

5 Conclusion

The comprehensive evaluation of propagation strategies for *Coleus forskohlii* (Briq.) underscores its standing as a premier medicinal resource, primarily due to the unique pharmacological profile of forskolin. As the global demand for natural adenylate cyclase activators grows, the limitations of traditional vegetative propagation such as low multiplication indices, high susceptibility to soil-borne pathogens, and seasonal dependency have become significant bottlenecks for the pharmaceutical supply chain.

This review identifies a critical shift toward biotechnological interventions as the most viable path forward. The synthesis of current research demonstrates that:

- (1) Micropropagation Efficiency: In vitro protocols, specifically direct organogenesis from leaf lamina and apical meristem culture, offer a robust mechanism for the rapid turnover of disease-free, genetically uniform planting material. The optimization of BAP and NAA concentrations remains the most effective hormone regime for maximizing shoot induction.
- (2) Regenerative Innovation: Somatic embryogenesis has emerged as a high-efficiency alternative, with maturation rates reaching 80%. This method provides a sophisticated platform for germplasm conservation and large-scale clonal propagation that exceeds the capacity of conventional stem cuttings.
- (3) Enhanced Phytochemistry: The integration of brassinosteroids and elicitors (such as methyl jasmonic acid) during the culture process not only facilitates superior rooting but also significantly enhances the biosynthetic pathways of secondary metabolites, leading to higher forskolin concentrations.
- (4) Sustainability and Scaling: Advanced cultivation techniques, including hairy root cultures and shake-flask bioreactors, present a sustainable model for metabolite extraction that bypasses the need for destructive harvesting of wild or field-grown plants.

In conclusion, while field-level optimizations like the "ridge and furrow" method provide incremental gains in yield, the future of *C. forskohlii* lies in the synergy between tissue culture technology and molecular elicitation. Adopting these biotechnological frameworks is essential for ensuring a consistent, high-quality supply of forskolin while simultaneously preserving the genetic diversity and sustainability of this endangered medicinal species. Future research should prioritize the refinement of bioreactor parameters and the exploration of genetic markers to further stabilize forskolin yields in commercial-scale production.

Authors' contributions

Sanjaai Kumar and Santhosh Raj conducted the literature review, collected the data regarding various propagation methods, and drafted the manuscript. Jones Ponuraj conceived of the study, participated in its design and coordination, and helped to draft the manuscript. All authors read and approved the final manuscript.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Belniaki A.C., Rabel L.A.D.N., Gomes E.N., and Zuffellato-Ribas K.C., 2018, Does the presence of leaves on coleus stem cuttings influence their rooting?, Ornamental Horticulture, 24: 206-210.
<https://doi.org/10.14295/oh.v24i3.1204>
- Bhat S.V., Bajqwa B.S., Dornauer H., do Seusa N.D., and Fehlhaber H.W., 1977, Structures and stereochemistry of new labdane diterpenoids from *Coleus forskohlii* Briq., Tetrahedron Letters, 18(19): 1669-1672.
[https://doi.org/10.1016/S0040-4039\(01\)93245-9](https://doi.org/10.1016/S0040-4039(01)93245-9)
- Biondi S., and Thorpe T.A., 1982, Clonal propagation of forest tree species, In Proceedings COSTED Symposium on Tissue Culture of Economically Important Plants, Forest Research Institute Malaysia, pp. 197-204.
- Dodds J.H., and Roberts L.W., 1982, Experiments in plant tissue culture, Cambridge University Press, Cambridge, London, New York.
- Dode L.B., Bobrowski V.L., Braga E.J.B., Seixas F.K., and Schuch M.W., 2003, In vitro propagation of *Ocimum basilicum* L. (Lamiaceae), Acta Scientiarum Biological Sciences, 25(2): 435-437.
<https://doi.org/10.4025/actascibiolsci.v25i2.2034>
- Gopi C., and Mary M.R., 2014, In vitro plant regeneration through somatic embryogenesis in medicinally important leaf explants of *Coleus forskohlii* Briq., IOSR Journal of Agriculture and Veterinary Science, 7(9): 20-23.
<https://doi.org/10.9790/2380-07912023>

- Govindaraju S., and Arulselvi P.I., 2018, Effect of cytokinin combined elicitors (l-phenylalanine, salicylic acid and chitosan) on in vitro propagation, secondary metabolites and molecular characterization of medicinal herb-*Coleus aromaticus* Benth (L), Journal of the Saudi Society of Agricultural Sciences, 17(4): 435-444.
<https://doi.org/10.1016/j.jssas.2016.11.001>
- Krishna G., Sairam Reddy P., Anoop Nair N., Ramteke P.W., and Bhattacharya P., 2010, In vitro direct shoot regeneration from proximal, middle and distal segment of *Coleus forskohlii* leaf explants, Physiology and Molecular Biology of Plants, 16: 195-200.
<https://doi.org/10.1007/s12298-010-0021-y>
- Krombholz R., Mersinger R., Kreis W., and Reinhard E., 1992, Production of forskolin by axenic *Coleus forskohlii* roots cultivated in shake flasks and 20-l glass jar bioreactors, Planta Medica, 58(4): 328-333.
<https://doi.org/10.1055/s-2006-961478>
- Lisowska K., and Wysokinska H., 2000, In vitro propagation of *Catalpa ovata* G. Don, Plant Cell, Tissue and Organ Culture, 60: 171-176.
<https://doi.org/10.1023/A:1006461520438>
- Murashige T., and Skoog F., 1962, A revised medium for rapid growth and bio assays with tobacco tissue cultures, Physiologia Plantarum, 15(3).
<https://doi.org/10.1111/j.1399-3054.1962.tb08052.x>
- Patel D.K., 2016, Vegetative propagation of *Coleus forskohlii* (Willd) Briq using their stem cutting for ex-situ conservation in herbal garden, Medicinal and Aromatic Plants Research, 5(261): 2167-0412.
- Rao C.C., Chandrasekhar R., and Rajkumar M., 2016, Studies on the effect of plant density and method of planting on leaf area of medicinal coleus [*Coleus forskohlii* (Willd) Briq.], Advances in Life Sciences, 5(6): 2204-2206.
- Rupp R.H., de Souza N.J., and Dohadwalla A.N., 1986, Proceedings of the international symposium on forskolin: its chemical, biological and medicinal potential, Hoechst India Limited, Bombay.
- Sahai A., and Shahzad A., 2010, In vitro clonal propagation of *Coleus forskohlii* via direct shoot organogenesis from selected leaf explants, Journal of Plant Biochemistry and Biotechnology, 19: 223-228.
<https://doi.org/10.1007/BF03263344>
- Sairam Reddy P., Rodrigues R., and Rajasekharan R., 2001, Shoot organogenesis and mass propagation of *Coleus forskohlii* from leaf derived callus, Plant Cell, Tissue and Organ Culture, 66: 183-188.
<https://doi.org/10.1023/A:1010697813852>
- Seamon K.B., and Daly J.W., 1981, Forskolin: a unique diterpene activator of cyclic AMP-generating systems, Journal of Cyclic Nucleotide Research, 7(4): 201-224.
- Sen J., Sharma A.K., Sahu N.P., and Mahato S.B., 1992, Production of forskolin in in vitro cultures of *Coleus forskohlii*, Planta Medica, 58(4): 324-327.
<https://doi.org/10.1055/s-2006-961477>
- Sharan A.K., Singh B.P., Dubey S.R., Kumar R., Kishor A., Kumar G., and Kumari S., 2014, Effective propagation and evaluation of salt tolerance in *Coleus forskohlii*, an endangered herb, International Journal of Advanced Science Engineering Technology, 3(2): 24-31.
- Sharma N., Chandel K.P.S., and Srivastava V.K., 1991, In vitro propagation of *Coleus forskohlii* Briq., a threatened medicinal plant, Plant Cell Reports, 10: 67-70.
<https://doi.org/10.1007/BF00236459>
- Shrivastava S., and Banerjee M., 2008, In vitro clonal propagation of physic nut (*Jatropha curcas* L.): influence of additives, International Journal of Integrative Biology, 3(1): 73-77.
- Swamy K.N., and Rao S.S.R., 2011, Effect of brassinosteroids on the performance of coleus (*Coleus forskohlii*), Journal of Herbs, Spices and Medicinal Plants, 17(1): 12-20.
<https://doi.org/10.1080/10496475.2011.556985>
- Yanagihara H., Sakata R., Minami H., Tanaka H., Shoyama Y., and Murakami H., 1996, Immunoaffinity column chromatography against forskolin using an anti-forskolin monoclonal antibody and its application, Analytica Chimica Acta, 335(1-2): 63-70.
[https://doi.org/10.1016/S0003-2670\(96\)00371-6](https://doi.org/10.1016/S0003-2670(96)00371-6)
- Yasmin R., Javed F., and Arfan M., 2001, Somatic embryogenesis in callus culture of wheat (*Triticum aestivum* L.) accession 235/2, International Journal of Agriculture and Biology, 3: 163-166.

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Research Article

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The Effect of Stem Recutting and Floral Food on Vase Life of *Zinnia elegans*

Lauren E. Baskin¹, Coleman L. Etheredge¹ ✉, James DelPrince², Tongyin Li¹, Myles Landers³¹ Department of Plant and Soil Sciences, Mississippi State University, 75 B. S. Hood Rd., Mississippi State, MS 39762, USA² Mississippi State University Coastal Research and Extension Center, Mississippi State University, 1815 Popp's Ferry Rd., Biloxi, MS 39532, USA³ College of Business, Mississippi State University, 75 B. S. Hood Rd., Mississippi State, MS 39762, USA✉ Corresponding author: cle248@msstate.eduInternational Journal of Horticulture, 2026, Vol.16, No.3 doi: [10.5376/ijh.2026.16.0013](https://doi.org/10.5376/ijh.2026.16.0013)

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Abstract Locally grown specialty cut flowers require species-specific postharvest handling recommendations to maintain flower quality and extend vase life. Knowing the best care for flowers once removed from the mother plant is crucial information for farmers, florists, and the common consumer, as this will affect the longevity of the product and happiness of the consumer. This research examined zinnias variation in vase life between the following test groups: zinnias with untrimmed stems in tap water, zinnias with trimmed stems in tap water, zinnias with untrimmed stems in floral food solution, and zinnias with trimmed stems in floral food solution Across both harvests, recut stems held in floral food had the longest average vase life (16.46 d), followed by non-recut stems in floral food (14.70 d), non-recut stems in tap water (12.80 d), and recut stems in tap water (11.70 d). If adding a floral solution to the water is not an option, then the stems should be left untrimmed. Overall, the stems in tap water that were trimmed had the shortest vase life, and the stems in floral food solution that were trimmed lived the longest out of any of the groups.

Keywords Floral preservatives; Flower food; Locally grown; Specialty cut flowers; Vase life; *Zinnia elegans*

1 Introduction

The cut flower industry is dynamic and evolving as there have been many shifts in the current times and trends. One trend is the specialty cut flower movement. Specialty-cut flowers are defined as those that are locally produced in small quantities and stored for short time frames; compared to traditional cut flowers, which are produced in mass quantities and shipped globally (Darras, 2021). Specialty cut flower farmers can greatly profit from these niche plants, as one acre of properly maintained land can generate \$25,000 to \$30,000 in revenue annually (Byczynski, 2008). An example of a specialty cut flower that can be grown locally is the zinnia, *Zinnia elegans*. Zinnias show an opposite leaf pattern and range in wide varieties of colors with solid, variegated, and bicolor cultivars (Song et al., 2025). These flowers can exhibit a wide variety of flower structures, ranging from very simple petal arrangements to complex petal florets (Song et al., 2025). Zinnias are disease-resistant, when watered in a manner that prevents water from standing on the leaves (Esringü et al., 2022). They should be cultivated in areas with well-draining, fertile soil that receive a minimum of 8 hours of full sun (Fitzpatrick et al., 2024). A balanced fertilizer may be applied throughout the growing season, should the soil have any nutrient deficiencies, to ensure the plants flourish. Zinnias should be harvested just before full maturity, when blooms are almost fully opened, and placed in cool water with a small amount of floral preservative to ensure a maximum vase life for consumers (Laschkewitsch and Smith, 2000).

While many studies have been conducted on the vase life of *Zinnia elegans* (Carlson et al., 2015; Kalinowski et al., 2022), recent research has shown that the vase life of Zinnia may be negatively affected by a commonly recommended practice, cutting the ends of stems frequently (Kalinowski et al., 2022). These recent findings call into question specifically when zinnia stems should be cut to extend their vase life. The vase life of cut flowers is a critical factor in both the commercial floriculture industry and home floral use, directly influencing customer satisfaction and economic value. Once cut from the mother plant fresh cut flowers have a limited supply of sugars and water stored in their stems and leaves and require supplemental sugars and water supply to maintain flower health and prolong vase life (Pun and Ichimura, 2003). To maintain the longest possible vase life, it is

recommended that flower preservatives be added to the water when storing and arranging cut flowers (Nguyen and Lim, 2021). Flower preservatives are specifically formulated for cut flower use and are comprised of three main ingredients; sugars, acidifiers, and biocides (Da Silva, 2003; Nguyen and Lim, 2021). Flower preservatives enhance water absorption by lowering the pH of the solution, suppress microbial development, and supply carbohydrates necessary for the metabolic processes of cut flowers (Han 2003; Nguyen and Lim, 2021). In a study completed by (Iqbal et al., 2012), researchers studied zinnias placed in water with various levels of preservation enhancers, Indole-3-acetic acid (IAA), 1-naphthylacetic acid (NAA), and salicylic acid (SA), it was found that salicylic acid was the most beneficial to the flowers, maintaining the longest average vase life. Additionally, it has been found adding a solute such as aluminum sulfate to the water can enhance water uptake and extend the vase life of zinnias (Kalinowski et al., 2022). Blockage of the xylem vessels can hinder water uptake in cut flowers, this can be caused by various factors such as bacterial proliferation and pinched or damaged stems (Chen et al., 2023). Past research has found that bacterial build up can shorten flower life and cause inferior flower quality (Balestra et al., 2005; Jowkar 2015). Bacterial organisms contribute to the breaking down of cells at the end of flower stems, thus creating an obstruction in a flowers vascular system, slowing water uptake. Stems obstruction may also occur due to injuries to the stem during harvest (Dixon and Peterson, 1989). Wound-induced xylem occlusion is a condition that has been found to affect some species of cut flowers (Manzoor et al., 2024). Wound occlusions have been found to occur as a stress response when a flowers stem is cut (Manzoor et al., 2024). Symptoms of water stress due to stem blockage or damage often present as wilting of the flower petals or bending in the neck of the flower, the area just below the flower structure (Dixon and Peterson, 1989).

While various factors can influence the longevity of cut flowers, two commonly recommended practices; recutting stems after harvesting and adding floral food to vase water are widely used to enhance vase life (Nell and Reid, 2001; Ahmad and Dole, 2014; Kalinowski et al., 2022). However, recent research has indicated that recutting zinnia stems once cut from the mother plant can reduce the overall vase life of the flower in certain instances (Kalinowski et al., 2022). These findings leave questions regarding best post-harvest practices for *Zinnia elegans*.

The purpose of this study was to investigate how stem cutting and the application of floral food affect the vase life of *Zinnia elegans*. Specifically, the study aims to determine whether cutting the ends of the stems enhances flower longevity, whether floral food extends vase life when used with both cut and uncut stems, and to identify which combination of these treatments results in the greatest extension of vase life for *Zinnia elegans*. By comparing the effects of these common postharvest practices, the study seeks to provide evidence-based recommendations for improving the freshness and ornamental value of *Zinnia elegans* in vase arrangements.

2 Materials and Methods

2.1 Zinnia propagation protocol

The seeds for this study were purchased from Johnny's Selected Seeds, and the variety was Benary's Giant Deep Red. The zinnia seeds were initially planted on May 27th, 2025, in 72 cell seed trays, for a total of 864 possible plants. The seeds were then placed in greenhouses located on Mississippi State University campus for 4 weeks to germinate. After the initial 4-week germination period, the seedlings were transplanted into raised beds located in the Thad Cochran research center at Mississippi State University's on June 25th, 2025. Each seedling was planted approximately 15 cm apart in soil consisting of a mixture of topsoil and humus. There were 400 seedlings planted over 11 beds. Each raised bed was equipped with soaker hoses, allowing the plants to receive adequate water during their growing season. Plants received one application of an all-purpose fertilizer (Expert Gardner 10-10-10, Fort Lauderdale, FL). The fertilizer was evenly spread over the raised bed and worked into the top 5-10 cm of soil.

2.2 Zinnia harvest protocol

For this study, zinnia stems were harvested when the outer petals fully expanded and one row of florets opened (Kalinowski et al., 2022). Zinnia stems were cut to a uniform length (45 cm) and placed in tap water to maintain hydration overnight (Kalinowski et al., 2022). The zinnias were left to hydrate in a plastic bucket of tap water at

room temperature for one hour before being placed in a floral cooler set at 7 °C for 24 hours to ensure the flowers were properly hydrated before the experiment. The plastic buckets used in this experiment were sanitized with a bleach and water solution prior to the start of the experiment. A total of 200 flowers over two harvests were studied. The first round of 100 flowers was harvested on September 2nd, 2025, and after the 24-hour hydration process, the study began on September 3rd. The second harvest of 100 flowers took place on September 16th, 2025, and the study began on September 17th. There were exactly 2 weeks between the harvest dates.

2.3 Experimental protocol

The experiment was conducted as a 2×2×2 factorial design with vase solution, stem recutting treatment, and harvest date as factors. Each of the four treatment groups had 5 replicates (vases), making a total of 20 vases, 5 flowers per vase, per harvest. All vases were made of clear glass, cylindrical in shape, 19 cm high with an 8.5 cm diameter opening. Treatments were replicated across two harvests collected two weeks apart from the same zinnia plants. Flowers were randomized within each treatment group to reduce bias.

The following are the four independent groups the zinnias were randomly assigned to:

- (1) Stems placed in tap water and left untrimmed;
- (2) Stems placed in tap water and trimmed at an angle;
- (3) Stems placed in tap water with floral food (Floralife, Flower Food 300) and left untrimmed;
- (4) Stems placed in tap water with floral food and stems trimmed at an angle.

The tap water groups were each filled with 355 mL of water measured out with a measuring cup. The floral food solution groups were filled with 355 mL of the solution. The floral solution was prepared by mixing the powdered floral preservative with tap water at 10 g/L. The floral preservative used in this study was FloraLife original 300 flower food (FloraLife, Kent, Ohio). The room in which the experiment took place had an average air temperature of 21 °C with an average 18.29 μmol/m²/s of light available for 12 h/d at 50% to 60% relative humidity. Vases were placed away from heating, ventilation, and air conditioning systems within the room and remained stationary, not being randomly rotated, during the monitoring and evaluation of the vase life of the zinnias. The water and flower food solution was changed in all vases across all treatments every 3 d, with floral food added back into the vases within floral food treatment groups. A new floral preservative solution was made each time the water was replaced in the vases, the pH of the water was not tested. The zinnias within the treatment groups that received additional stem cuttings had approximately 2.54 cm trimmed off the bottom of their stems every 2 d from the time of harvesting.

2.4 Experiment monitoring and evaluation

Flower quality was monitored every 24 hours and evaluated using established protocols in previous studies investigating cut flower vase life longevity (Jones and Hill, 1993; Clark et al., 2010; Aalifar, 2020). Stems were discarded when 50% of the flower was wilted, petals dropped or had turned brown/discolored and/or neck bending/drooping, drying or general stem decline, and/or mold growth of any kind was observed on the flower (Jones and Hill, 1993; Clark et al., 2010; Aalifar, 2020; Kalinowski et al., 2022).

2.5 Data analysis

Data from the survey were entered into IBM SPSS Statistics (version 30; IBM Corp., Armonk, NY, USA) and analyzed using analysis of variance (ANOVA) tests, post hoc Duncan's multiple range test, and frequency statistics.

3 Results and Analysis

3.1 Vase life findings for first harvest of *Zinnia elegans*

ANOVA tests were used to determine if there were differences in vase life between the treatment groups. Significant differences were found in the minimum, maximum, and average vase life within the first harvest. Post hoc tests were used to determine where these differences occurred. Zinnia stems that did not receive a stem cutting and were placed in tap water and stems that did receive a cutting in tap water showed similarities between the test

groups, both had a minimum vase life of 8 d (Table 1). Zinnia stems that did not receive a stem cutting and placed in floral food solution and stems that did receive a cutting in floral food solution also showed similarities between the test groups, as they also shared a similar minimum vase life of 12 d and 11 d, respectively (Table 1). There were differences between tap water and floral food solution test groups, as the vase life varies by 3-4 d between the two groups. The zinnias within the flower food solution groups were found to live longer than zinnias in the tap water groups.

Table 1 Vase life of cut *Zinnia elegans* flowers under four postharvest treatments during the first harvest

Dependent variable	No cut + tap water	Cut + tap water	No cut + flower food	Cut + flower food	df	F value	P value
Minimum days	8 ^a	8 ^a	12 ^b	11 ^b	3	9.790	0.001*
Maximum days	21 ^b	15 ^a	20 ^b	22 ^c	3	12.333	0.001*
Average days	13.56 ^b	11 ^a	15.24 ^b	16.76 ^c	3	25.395	0.001*

Note: *Significant at $P \leq 0.05$, Means within a row followed by different lowercase letters are significantly different according to Duncan's multiple range test at $P \leq 0.05$

Regarding the differences in maximum vase life, it was found zinnia stems that did receive a stem cutting and placed in tap water had a maximum vase life of 15 d, while stems that did receive a cutting and placed in floral food solution had a maximum vase life of 22 d (Table 1). Untrimmed stems in tap water and untrimmed stems placed in floral food showed similarities between the groups, having similar maximum vase lives of 21 d and 20 d, respectively (Table 1).

When analyzing the average number of days flowers remained alive in each treatment group, it was found zinnia stems that did receive a stem cutting and placed in tap water and stems that did receive a cutting and placed in floral food solution were significantly different from all the other groups and each other. The zinnias that were cut and placed in tap water had an average vase life of 11 d, while the zinnias that were cut and placed in a flower food solution had an average of 16.76 d, a difference of 5.76 d.

3.2 Vase life findings for second harvest of *Zinnia elegans*

ANOVA tests were run on the data to determine any differences between the test groups, looking specifically at vase life. Significant differences were found within the second harvest treatment groups based on their maximum, minimum, and average vase life. Post hoc tests examined where these differences occurred. Test results revealed that the uncut stems in tap water and the cut stems in tap water showed similarities, as the two trials shared a minimum vase life of 7 d. The cut stems in tap water and uncut stems in flower food showed statistical similarities in the study. Uncut stems in a floral food solution and cut stems in floral food solution showed similarities, as they had a minimum vase life of 10 d and 9 d, respectively (Table 2).

Table 2 Vase life of cut *Zinnia elegans* flowers under four postharvest treatments during the second harvest

Dependent variable	No cut + tap water	Cut + tap water	No cut + flower food	Cut + flower food	df	F value	P value
Minimum days	7 ^a	7 ^{ab}	10 ^{bc}	9 ^c	3	6.202	0.005*
Maximum days	19 ^a	19 ^{ab}	21 ^{bc}	21 ^c	3	5.920	0.006*
Average days	12.04 ^a	12.40 ^a	14.16 ^b	16.16 ^b	3	13.920	0.001*

Note: *Significant at $P \leq 0.05$, Means within a row followed by different lowercase letters are significantly different according to Duncan's multiple range test at $P \leq 0.05$

ANOVA also indicated differences in the maximum vase life for zinnias in the second harvest based on the treatment groups. Post hoc analysis found the uncut zinnia stems in tap water and cut stems in tap water showed similarities between the test groups. These two trials shared a maximum vase life of 19 d. The cut stems placed in tap water and uncut stems placed in a floral food solution showed similarities in their test groups as well. These two test groups had a difference between the maximum vase life of 2 d. The uncut stems and trimmed stems both placed in the floral food solution showed similarities, as their maximum vase life was both 21 d.

When comparing the average vase life between the four treatment groups, ANOVA showed that uncut and cut stems placed in tap water had similarities between the trials within the second harvest test group, as did uncut and cut stems placed in a floral food solution. While there were differences between tap water and floral food trials, the variation between uncut stems versus cut stems placed in tap water had an average vase life difference of 0.36 d. The difference between the floral food solution groups, both uncut and cut stems, was 2 d. However, the two flower food groups both average higher vase life than the tap water groups by 1.76-4.12 d.

3.3 Vase life findings for combined harvest data of *Zinnia elegans*

The data from both harvests was combined and analyzed as a whole to determine if there were differences in the treatment groups based on the collective data for all 200 flowers. ANOVA tests were run on the data to determine any differences in vase life among the test groups. Significant differences were found between the maximum, minimum, and average vase life based on the treatment group the flowers were placed. Post hoc tests used to determine where these differences occurred. ANOVA revealed that the uncut stems and the cut stems across all test subjects placed in tap water showed similarities, as well as uncut stems and the cut stems across all test subjects placed in a floral food solution showed similarities. It is important to note that the differences were between the water type, tap water and floral food, rather than between the factor of if the zinnia stem was trimmed or not. In both tap water groups, the overall minimum day was 7 d, while the floral food solution test group's minimum days were 10 d for uncut and 9 d for cut stems. This is 2-3 d longer than the minimum for both tap water test groups (Table 3).

Table 3 Combined vase life from harvest one and two of cut *Zinnia elegans* flowers under four postharvest treatments

Dependent variable	No cut + tap water ¹	Cut + tap water	No cut + floral food	Cut + floral food	df	F value	P value
Minimum days	7 ^a	7 ^a	10 ^b	9 ^b	3	12.979	0.001*
Maximum days	21 ^{ab}	19 ^a	21 ^b	22 ^c	3	13.046	0.001*
Average days	12.8 ^a	11.7 ^a	14.7 ^b	16.46 ^c	3	27.096	0.001*

Note: *Significant at $P \leq 0.05$; ¹ Average over 2 replications; Means within a row followed by different lowercase letters are significantly different according to Duncan's multiple range test at $P \leq 0.05$

When analyzing the maximum vase life, it was found the uncut stems placed in tap water showed similarities between both cut stems in tap water and uncut stems in floral food solution, however, cut stems in tap water and uncut stems in floral food indicated differences from each other. Both uncut stems in tap water and uncut stems in floral food had a maximum vase life of 21 d. The cut stems and uncut stems in tap water were also found to be similar, having a difference of 2 d in maximum vase life. In this trial, the cut stems in the floral food solution were significantly different from all the other test groups, having the longest vase life of 22 d (Table 3).

ANOVA revealed that for average vase life, there were similarities between uncut and cut stems that were placed in tap water. Both the uncut stems and the cut stems that were placed in the floral food solution differed from each other as well as the tap water groups. The average vase life for uncut stems in tap water was 12.8 d and cut stems in tap water was 11.7 d, a difference of 1.1 d. Conversely, the uncut stems in the floral food solution group lived an average of 14.7 d and cut stems in the floral food solution averaged 16.46 d.

3.4 Comparison of vase life between harvest groups

ANOVA tests were used to determine if there were any differences in the vase life of the zinnias between the first and second harvest group. No statistically significant differences were found between the maximum, minimum, or average days of vase life between the first and second harvest groups, indicating that vase life between harvests was relatively the same (Table 4).

Table 4 Comparison of the differences in vase life of fresh cut zinnias between harvest one and harvest two

Dependent variable	df	Mean Square	F Value	P Value
Minimum days	1	14.40	3.283	0.078
Maximum days	1	1.225	0.142	0.709
Average days	1	1.806	0.379	0.542

4 Discussion

Overall, it was found that the use of flower food extended the vase life of *zinnia elegans* regardless of if the stems were trimmed or not. Trimming the stems of zinnias that were placed in the floral preservative solution was found to extend the vase life the longest. Past studies have found that floral food prolongs the vase life of various fresh cut flowers (Asrar, 2012; Nguyen and Lim, 2021; Zeng et al., 2023). Findings from this study indicated there were significant differences between zinnias that were trimmed and placed into tap water in the first harvest when compared to all other treatment groups within the first harvest, however this was not consistent with findings from the second harvest or when the flowers from both harvests were looked at collectively. Though it was not found to be significantly different, when the zinnias were looked at collectively, overall, the zinnias that were placed in tap water and had their stems cut had the shortest vase life when compared to all other groups. These findings support past research completed by (Kalinowski et al., 2022) which stated that leaving the stems in tap water untrimmed will slightly lengthen the vase life of *Zinnia elegans*. This would indicate that should floral food not be available for use, then the proper recommendation for *Zinnia elegans* is to leave the stems untrimmed in tap water. The shortened vase life that was observed when cutting stems placed in tap water could be a result of a wound-induced xylem occlusion, which occurs in some flowers species due to a stress response when their stems are cut (Manzoor et al., 2024).

No significant differences were found in the vase life of the zinnia between the two separate harvests. Previous research has found that earlier harvests of zinnias had longer vase lives than those bloom that were harvested later in the growing season (Kalinowski et al., 2022). Only two harvests taken two weeks apart were used in this study. Results investigating vase life between harvests from this study could have potentially changed if additional harvests of zinnia been investigated or more time had passed between harvests. Additional harvests over an extended time period should be investigated in similar future research studies.

Retail florists, specialty cut flower farmers, educators, and home gardeners can all benefit from this research. Proper post-harvest techniques are critical to implement immediately upon cutting the blooms from the mother plant. From a cut flower farmer perspective, it is important to properly hydrate the stems and know how to care for the zinnias before sending them out to buyers, markets, or selling them. Farmers may also benefit from sharing the proper care techniques with the buyers to ensure longevity of vase life in the retail setting. Home gardeners and consumers of fresh cut zinnias could potentially benefit the most from this knowledge, as flower preservatives for fresh cut flowers are not commonly purchased by the general population. Publishing updated tips on keeping zinnias looking fresh for the longest amount of time that are written for and accessible to the general public should be considered. Extension services that offer classes on cut flower cultivation and floral design is another way to share the proper post-harvest protocol for zinnia when handling them in the absence of floral preservatives with the public.

5 Conclusions

Findings from this study indicated that the use of floral preservatives in combination with trimming the ends of the stems significantly increases the vase life of *zinnia*. Additionally, differences were observed in the vase life of zinnias placed in tap water based on whether their stems were trimmed or not, with trimmed stems exhibiting the shortest overall vase life compared to all other treatment groups. These findings suggest that, in situations where floral preservative solutions are unavailable, the recommended postharvest handling practice for *Zinnia elegans* may be to leave stems untrimmed to maximize vase life. Results may not apply to other flower species, as *Zinnia elegans* may respond differently to treatments than other cut flowers. Also, the study focused only on postharvest

conditions over a limited period and does not account for long-term storage or transportation factors affecting vase life. Based on the findings from this study it is recommended to study other cultivars of zinnias to see if they produce the same results using these treatments as well as other cut flower grown by small regional growers such as cosmos (*Cosmos bipinnatus*), sunflowers (*Helianthus*), marigolds (*Tagetes*), celosia (*Celosia argentea*) to investigate if other specialty cut flower species respond in a similar manner.

Authors' contributions

Lauren Baskin and Cole Etheredge were the principal researchers who conceptualized the research idea, collected, and analyzed the research data, and prepared the manuscript. James DelPrince, Tongyin Li, and Myles Landers assisted in analysis, verification, editing, and proofreading of the manuscript. All authors read and approved the final manuscript.

Conflict of Interest Disclosure

The authors declare that they have no competing interests.

References

- Aalifar M., Aliniaefard S., Arab M., Mehrjerdi M.Z., Daylami S.D., Serek M., Woltering E., and Li T., 2020, Blue light improves vase life of carnation cut flowers through its effect on the antioxidant defense system, *Frontiers in Plant Science*, 11: 511.
<https://doi.org/10.3389/fpls.2020.00511>
- Ahmad I., and Dole J.M., 2014, Homemade floral preservatives affect postharvest performance of selected specialty cut flowers, *HortTechnology*, 24(3): 384-393.
<https://doi.org/10.21273/horttech.24.3.384>
- Asrar A.W.A., 2012, Effects of some preservative solutions on vase life and keeping quality of snapdragon (*Antirrhinum majus* L.) cut flowers, *Journal of the Saudi Society of Agricultural Sciences*, 11(1): 29-35.
<https://doi.org/10.1016/j.jssas.2011.06.002>
- Balestra G.M., Agostini R., Varvaro L., Mencarelli F., and Bellincontro A., 2005, Bacterial populations related to Gerbera (*Gerbera jamesonii* L.) stem break, *Phytopathologia Mediterranea*, December 2005: 1000-1009.
https://doi.org/10.14601/Phytopathol_Mediterr-1798
- Byczynski L., and Wimbiscus R., 2013, *The flower farmer: an organic grower's guide to raising and selling cut flowers*, 2nd edition, Chelsea Green Publishing.
- Carlson A.S., Dole J.M., Matthyse A.G., Hoffmann W.A., and Kornegay J.L., 2015, Bacteria species and solution pH effect postharvest quality of cut *Zinnia elegans*, *Scientia Horticulturae*, 194: 71-78.
<https://doi.org/10.1016/j.scienta.2015.07.044>
- Chen Y.H., Miller W.B., and Hay A., 2023, Postharvest bacterial succession on cut flowers and vase water, *PLoS One*, 18(10): e0292537.
<https://doi.org/10.1371/journal.pone.0292537>
- Clark E.M., Dole J.M., Carlson A.S., Moody E.P., McCall I.F., Fanelli F.L., and Fonteno W.C., 2010, Vase life of new cut flower cultivars, *HortTechnology*, 20(6): 1016-1025.
<https://doi.org/10.21273/HORTTECH.20.6.1016>
- Da Silva J.T., 2003, The cut flower: postharvest considerations, *Journal of Biological Sciences*, 3(4): 406-442.
<https://doi.org/10.3923/jbs.2003.406.442>
- Darras A., 2021, Overview of the dynamic role of specialty cut flowers in the international cut flower market, *Horticulturae*, 7(3): 51.
<https://doi.org/10.3390/horticulturae7030051>
- Dixon M.A., and Peterson C.A., 1989, A re-examination of stem blockage in cut roses, *Scientia Horticulturae*, 38(3-4): 277-285.
[https://doi.org/10.1016/0304-4238\(89\)90075-7](https://doi.org/10.1016/0304-4238(89)90075-7)
- Esringü A., Ekinci M., and Turan M., 2022, Effects of different growing media on growth parameters of Zinnia (*Zinnia elegans*), *Yuzuncu Yıl University Journal of Agricultural Sciences*, 32(1): 175-185.
<https://doi.org/10.29133/yyutbd.1034425>
- Fitzpatrick E., Voyer H., Barnes A.R., and Lang K., 2024, Growth and quality of four Zinnia cultivars grown in eastern South Dakota, *HortTechnology*, 34(5): 585-593.
<https://doi.org/10.21273/HORTTECH05452-24>
- Han S.S., 2003, Role of sugar in the vase solution on postharvest flower and leaf quality of oriental lily 'Stargazer', *HortScience*, 38(3): 412-416.
<https://doi.org/10.21273/HORTSCI.38.3.412>
- Iqbal D., Habib U., Abbasi N.A., and Chaudhry A.N., 2012, Improvement in postharvest attributes of Zinnia (*Zinnia elegans* cv. Benarys Giant) cut flowers by the application of various growth regulators, *Pakistan Journal of Botany*, 44(3): 1091-1094.
- Jones R.B., and Hill M., 1993, The effect of germicides on the longevity of cut flowers, *Journal of the American Society for Horticultural Science*, 118(3): 350-354.
<https://doi.org/10.21273/JASHS.118.3.350>

- Jowkar M.M., 2015, Effects of chlorination and acidification on postharvest physiological properties of alstroemeria, cv. 'Vanilla' and on microbial contamination of vase solution, *Horticulture, Environment, and Biotechnology*, 56(4): 478-486.
<https://doi.org/10.1007/s13580-015-0022-4>
- Kalinowski J., Moody E.P., and Dole J.M., 2022, Improving hydration and vase life of cut Zinnia, *Scientia Horticulturae*, 293: 110661.
<https://doi.org/10.1016/j.scienta.2021.110661>
- Laschkewitsch B., and Smith R.C., 2000, Growing cut flowers for market, NDSU Extension Service, North Dakota State University.
- Manzoor A., Bashir M.A., Naveed M.S., Akhtar M.T., and Saeed S., 2024, Postharvest chemical treatment of physiologically induced stem end blockage improves vase life and water relation of cut flowers, *Horticulturae*, 10(3): 271.
<https://doi.org/10.3390/horticulturae10030271>
- Nell T.A., and Reid M., 2000, Flower and plant care: the 21st century approach, Society of American Florists.
- Nguyen T.K., and Lim J.H., 2021, Do eco-friendly floral preservative solutions prolong vase life better than chemical solutions?, *Horticulturae*, 7(10): 415.
<https://doi.org/10.3390/horticulturae7100415>
- Pun U.K., and Ichimura K., 2003, Role of sugars in senescence and biosynthesis of ethylene in cut flowers, *Japan Agricultural Research Quarterly: JARQ*, 37(4): 219-224.
<https://doi.org/10.6090/jarq.37.219>
- Song C., Liu X., Xu M., Ying M., Fu J., and Zhang C., 2025, Germplasm resource and genetic breeding of Zinnia: a review, *Ornamental Plant Research*, 5(1).
<https://doi.org/10.48130/opr-0025-0014>
- Zeng F., Xu S., Geng X., Hu C., and Zheng F., 2023, Sucrose + 8-HQC improves the postharvest quality of lily and rose cut flowers by regulating ROS-scavenging systems and ethylene release, *Scientia Horticulturae*, 308: 111550.
<https://doi.org/10.1016/j.scienta.2022.111550>

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Research Perspective

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Marker-assisted Selection in Soybean Breeding: Achievements and LimitationsHangming Lin ¹ ✉, Xiaoxi Zhou ²¹ Tropical Legume Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China² Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China✉ Corresponding author: hangming.lin@hitar.orgInternational Journal of Horticulture, 2026, Vol.16, No.3 doi: [10.5376/ijh.2026.16.0014](https://doi.org/10.5376/ijh.2026.16.0014)

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Abstract Soybean is a globally important crop for both food and oil production. However, traditional breeding relies heavily on phenotypic selection, which is time-consuming, inefficient, and highly influenced by environmental factors, making it difficult to achieve the coordinated improvement of high yield, superior quality, and stress resistance. This study systematically reviews the application progress of marker-assisted selection (MAS) in soybean breeding, including resistance to diseases and pests, tolerance to abiotic stresses, optimization of agronomic traits, and improvement of seed quality. It also analyzes the practical value of MAS in gene pyramiding and backcross breeding. The results indicate that MAS has clear advantages in tracking, introgressing, and pyramiding major genes and large-effect quantitative trait loci (QTL), thereby improving selection efficiency and shortening breeding cycles. However, for complex quantitative traits such as yield and wide adaptability, its effectiveness is still constrained by factors including minor-effect QTL, gene–environment interactions, and cost inputs. MAS serves as a fundamental technology for precision breeding in soybean. In the future, it should be integrated with genomic selection, multi-omics approaches, and gene editing technologies to enhance the improvement of complex traits and support the development of climate-resilient soybean varieties.

Keywords Soybean; Marker-assisted selection; Gene pyramiding; Quality improvement; Genomic selection

1 Introduction

Soybean (*Glycine max* (L.) Merr.) is an important crop used for both grain and oil production. It provides plant protein and oil for human food, animal feed, and industrial uses, and holds a highly important position in global agricultural production (Bhat and Yu, 2021; Xue et al., 2025). In recent years, with population growth, changes in dietary structure, and the expansion of animal husbandry and bio-based industries, global demand for soybean yield and quality has continued to increase (Vargas-Almendra et al., 2024). Climate change, emerging diseases, and limited arable land resources have also placed greater pressure on soybean production. Therefore, more efficient breeding methods are needed to develop new varieties with higher yield, better quality, and stronger stress resistance as soon as possible.

Traditional soybean breeding mainly relies on phenotypic selection and long-term field evaluation, and has achieved many results in genetic improvement. However, the overall breeding cycle is long, the labor demand is high, and the process is easily affected by the environment. These limitations are particularly evident in the improvement of complex quantitative traits such as yield, quality, and stress resistance (Ma et al., 2016; Bhat and Yu, 2021). With the development of molecular biology and genomics, introducing molecular genetic information into the breeding process has become an important approach to improving efficiency and shortening the breeding cycle.

Marker-assisted selection (MAS) has developed under this background. It uses DNA markers closely linked to target genes or quantitative trait loci (QTLs) to conduct indirect selection in breeding populations (Bhat and Yu, 2021). Compared with traditional phenotypic selection, MAS can complete genotypic identification at the seed or seedling stage, reduce repeated phenotypic evaluations, and improve screening efficiency (Lin et al., 2022). Commonly used markers currently include SSR, SNP, InDel, and KASP, which have been widely applied in

early-generation selection, marker-assisted backcrossing (MABC), and the pyramiding of favorable alleles (Li et al., 2024; Wang et al., 2024).

With the completion of soybean genome sequencing and the application of high-throughput genotyping platforms, such as SoySNP50K and BARCSoySNP6K, a large number of genes and QTLs controlling important agronomic traits, disease resistance, and seed quality have been gradually identified, laying a foundation for the application of MAS in soybean breeding (Ravelombola et al., 2021; Lin et al., 2022). For example, MAS for maturity E gene loci (E1-E4, etc.) has been successfully applied to the improvement of early-maturing adaptability in high-latitude regions (Yerzhebayeva et al., 2023); the prediction accuracy of SNP markers for pod shattering resistance, such as KSS-SNP5, can exceed 90% (Kim et al., 2020); and various SSR and KASP markers have also been developed to improve quality traits such as seed protein, oil content, and Kunitz trypsin inhibitor (Riaz et al., 2023; Li et al., 2024). Studies have shown that MAS has become an important conventional breeding strategy for introducing key genes into the genetic backgrounds of elite varieties.

Although MAS has made progress in soybean breeding, its application still faces certain limitations. Many important agronomic traits, especially yield-related traits, are usually controlled jointly by multiple loci with small effects and are influenced by gene–environment interactions. This limits the predictive ability of MAS based on a small number of marker loci (Zhang et al., 2016; Ravelombola et al., 2021). Recent studies have shown that, in the improvement of such complex traits, genomic selection (GS) based on whole-genome marker information has higher prediction accuracy. Therefore, modern breeding strategies are increasingly inclined to combine MAS with GS in order to fully exploit the complementary advantages of both approaches (Bhat and Yu, 2021; Miller et al., 2023).

This study systematically analyzes the research progress and practical application effects of MAS in the improvement of important soybean traits, with a focus on its application achievements in disease resistance, stress resistance, agronomic traits, and quality improvement. It also discusses the limitations of MAS in the improvement of complex quantitative traits and its potential integration with emerging technologies such as genomic selection, with the aim of providing a reference for optimizing future molecular breeding strategies in soybean.

2 Application of MAS in Major-Effect Traits

2.1 Disease and pest resistance

Disease and pest resistance is one of the categories of major-effect traits in soybean that is most suitable for marker-assisted selection (MAS). Soybean cyst nematode (SCN) is one of the most destructive diseases and pests worldwide, and breeding resistant varieties is considered the most economical and environmentally friendly control strategy. At present, *rhg1* and *Rhg4* have been successfully identified and have become core loci for SCN resistance improvement. SSR, SNP, CAPS, and KASP markers developed around these loci have been widely used for early-generation screening of breeding populations and pyramiding of resistance genes, thereby improving resistance durability and reducing dependence on a single resistance source (Lin et al., 2022; Qu et al., 2025).

In addition to SCN, *Phytophthora* root rot and soybean rust are also among the most mature disease types for MAS application. *Phytophthora* root rot, caused by *Phytophthora sojae*, is mainly controlled by the *Rps* gene series. Map-based cloning of *Rps11* has shown that major-effect disease-resistance genes can provide direct targets for the deployment of broad-spectrum resistance. Therefore, foreground selection and marker-assisted backcrossing using markers closely linked to *Rps1*, *Rps3*, *Rps6*, *Rps11*, and other genes have become effective strategies for introducing disease-resistance genes into elite genetic backgrounds (Lin et al., 2022). For soybean rust, pyramiding of the *Rpp* gene series has also been applied in breeding. However, because the pathogen *Phakopsora pachyrhizi* evolves rapidly and has complex pathotypes, relying only on a single major-effect gene makes it difficult to maintain long-term stable resistance. Therefore, a combined strategy of “major-effect genes + minor-effect QTLs” is more suitable.

In terms of insect pests, Rag series genes associated with traits such as resistance to soybean aphid have also been mapped and used for molecular detection, indicating that MAS is applicable not only to disease resistance, but also to the rapid introgression and pyramiding of major pest-resistance loci.

2.2 Abiotic stress tolerance

Abiotic stresses such as drought, salinity-alkalinity, high temperature, low temperature, and waterlogging continue to limit stable and increased soybean production. Under the background of climate change, both their frequency and damage intensity are increasing. Therefore, stress-resistance breeding has become an important direction in soybean improvement (Manghwar et al., 2022). Although most stress-resistance traits have quantitative genetic characteristics, recent GWAS and QTL mapping studies have identified a group of loci with relatively large effects in soybean, enabling MAS to conduct effective selection for certain key tolerance traits. Taking drought resistance as an example, related QTLs are mostly associated with root architecture, osmotic regulation, and the maintenance of redox homeostasis, and are closely related to yield and yield stability under drought conditions (Amangeldiyeva et al., 2025; Gai et al., 2025) (Figure 1). In addition, the practice of introducing drought-resistance QTLs through MAS in rice, which achieved yield improvement under stress conditions without an obvious yield penalty under normal environments, also provides methodological reference for drought-resistance breeding in soybean (Ramayya et al., 2021; Hassan et al., 2023).

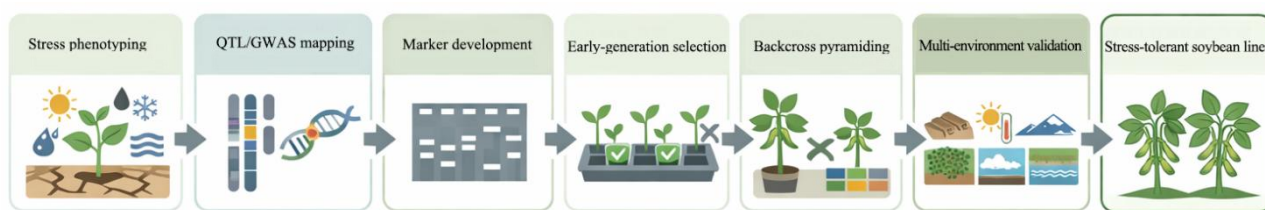


Figure 1 Molecular marker-assisted breeding workflow for soybean abiotic stress tolerance

Salinity-alkalinity stress is another key factor limiting regionalized soybean production. In addition to classical salt-tolerance loci, recent studies have further identified key genes such as *GmPM30*, whose favorable haplotypes can significantly improve survival and yield performance under salt stress by maintaining ion homeostasis and alleviating oxidative damage. The related haplotype-specific markers already have potential for application in MAS pipelines (Gai et al., 2025; Huang et al., 2025). In terms of waterlogging and heat tolerance, although their genetic bases are more complex, several major-effect QTLs or candidate regulatory genes associated with flooding survival rate, pollen viability, and flowering stability have been reported, such as *GmDREB*, *GmNAC*, *GmWRKY*, and *GmHSP*, indicating that MAS can still be used for targeted improvement around stable major-effect loci (Manghwar et al., 2022; Gai et al., 2025).

2.3 Agronomic trait improvement

Agronomic traits such as plant height, branching patterns, and growth habits directly affect light interception efficiency, lodging resistance, adaptability to mechanized harvesting, and final yield potential in soybean populations. Therefore, they are important targets for MAS of major-effect loci. GWAS and linkage analyses have identified multiple genomic regions associated with plant height and architecture in soybean, some of which overlap with determinate/indeterminate growth habit genes. The related SSR and SNP markers have been validated in breeding populations (Ravelombola et al., 2021; Podzorova et al., 2022). For example, SSR markers Satt244, Satt288, and Satt371 are significantly associated with plant height and related yield traits and can be used for early-generation selection of ideal plant-type materials, reducing lodging risk and improving population uniformity (Podzorova et al., 2022).

Flowering and maturity time are core traits determining regional adaptability of soybean, mainly regulated by photoperiod response genes such as *E1*, *E2*, *E3*, and *E4*. SNP markers closely linked to these loci have been used in breeding for adaptation to different ecological zones, allowing breeders to rapidly select genotypes with

appropriate growth periods according to target latitude and cropping system (Ravelombola et al., 2021; Gai et al., 2025). For yield-related traits, although total yield is a typical polygenic trait, component traits such as seed weight, pod number, and per-plant yield still contain QTLs with moderate to large effects. For example, an approximately 11.5 Mb region on chromosome 10 is significantly associated with both seed weight and yield, showing high breeding value (Ravelombola et al., 2021). Therefore, MAS can be preferentially applied for precise manipulation of major-effect agronomic traits such as plant architecture and growth period, and can be combined with genomic selection (GS) to simultaneously capture the contributions of both major- and minor-effect loci to yield potential (Ravelombola et al., 2021; Gai et al., 2025).

3 Application of MAS in Quality Improvement

3.1 Protein and oil content

Soybean seed protein and oil contents are core traits determining nutritional quality and processing value. Both traits have relatively high heritability, but they are usually negatively correlated with each other and show certain trade-offs with yield, making their coordinated improvement difficult (Lee et al., 2019). Existing GWAS, linkage analyses, and multi-environment trials have shown that although protein and oil contents are mainly controlled by multiple genes, relatively stable large-effect QTLs exist in regions such as chromosomes 15 and 20. In addition, several regions on chromosomes 2, 8, and 14 can also explain a relatively high proportion of phenotypic variation, and therefore have become priority targets for MAS utilization (Jin et al., 2023). These results indicate that, in quality breeding, MAS is particularly suitable for early-generation screening targeting stable major-effect loci, thereby improving the efficiency of identifying high-protein or high-oil materials.

In terms of oil improvement, high-resolution GWAS has identified multiple SNP-enriched regions associated with oil content, some of which contain candidate genes related to lipid metabolism and transport. Meta-QTLs formed through meta-analysis of previous QTLs further improve the stability and transferability of markers (Kumar et al., 2022). Among them, *GmSWEET39* on chromosome 15 has been identified as an important causal gene simultaneously affecting the protein-oil balance. Its different haplotypes correspond to “high-oil and low-protein” or “relatively high-protein” phenotypes, providing a functional marker basis for the targeted design of quality combinations (Figure 2) (Zhang et al., 2020). Therefore, by jointly tracking major-effect QTLs and key genes through functional markers such as KASP, MAS can, to a certain extent, alleviate the negative correlation between protein and oil and achieve targeted optimization of seed composition (Patel et al., 2025).

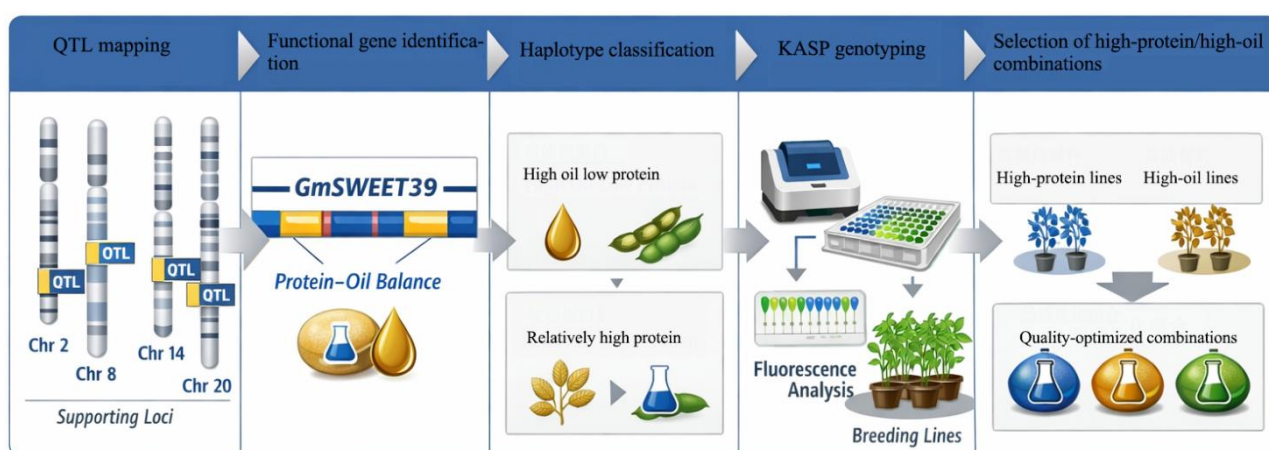


Figure 2 Functional marker-assisted optimization of soybean seed protein–oil balance based on *GmSWEET39* and major QTL

3.2 Specialized metabolites

In addition to protein and oil, soybean seeds are also rich in various specialized metabolites with nutritional and functional value, among which isoflavones and specific fatty acid compositions are the most representative. Isoflavones, such as genistein and daidzein, are synthesized through the phenylpropanoid-flavonoid pathway, and their natural variation is closely related to differences in the expression of key enzyme genes such as CHS, CHI,

and IFS, as well as upstream regulatory factors (Kim et al., 2021; Zhao et al., 2025). Transcriptomic and multi-omics studies have shown that related biosynthetic genes are continuously highly expressed at specific developmental stages in high-isoflavone lines, and isoflavone accumulation is also coordinated with changes in amino acid metabolism, lipid metabolism, and antioxidant defense networks. Therefore, molecular markers linked to or functionally associated with these loci can provide an important basis for the targeted improvement of isoflavone content through MAS.

Fatty acid composition directly determines the nutritional structure, oxidative stability, and processing suitability of soybean oil. High-resolution mapping studies have identified multiple stable QTLs controlling the contents of palmitic acid, stearic acid, oleic acid, linoleic acid, and linolenic acid, including candidate genes such as GmFabG, GmACP, GmFAD8, and fatty acid desaturase-related regions. These QTLs and their tightly linked SNPs can be directly used to screen high-quality oil-type materials, such as those with high oleic acid and low linolenic acid contents (Li et al., 2017; Kumar et al., 2022; Wang et al., 2025).

3.3 Seed nutritional and processing quality

Seed nutritional and processing quality directly determines the application value of soybean in soybean products, plant protein, and feed processing. Its improvement goals have expanded from simply increasing total protein content to optimizing amino acid composition, reducing antinutritional factors, and improving processing suitability. GWAS studies have shown that the contents of essential amino acids such as cysteine, methionine, lysine, and threonine are regulated by multiple QTLs, and some loci are relatively independent of total protein content loci. This means that amino acid balance can be improved through MAS without significantly changing the overall protein level (Lee et al., 2019). In addition, in populations derived from cultivated soybean and wild soybean, some donor alleles that increase protein content have been mapped and shown to function stably with relatively small effects on oil content and agronomic traits, providing traceable targets for backcross introgression and early-generation screening (Huang et al., 2020).

Trypsin inhibitors, lipoxygenases, and certain storage protein variants are important targets for MAS because they affect protein digestibility, beany flavor, oil oxidative stability, and functional properties in food processing, respectively (Kumar et al., 2022; Yao et al., 2022). Molecular markers closely linked to these loci can be used to screen materials with low antinutritional factors, reduced off-flavor, and better processing performance, thereby achieving coordinated improvement of nutritional quality and processing quality. As QTLs related to protein, oil, amino acids, and processing traits are gradually integrated with genomic prediction models, breeders have been able to design ideal genotypes around the comprehensive goals of “high nutritional value-excellent processing characteristics-acceptable agronomic performance” (Sun et al., 2022; Patel et al., 2025).

4 Gene Pyramiding and MAS

4.1 Gene pyramiding strategies

Gene pyramiding refers to a breeding strategy that integrates multiple independent genes or QTLs with favorable effects into the same genetic background, aiming to simultaneously express multiple desirable traits in a single variety, thereby achieving broader, more stable, or more durable improvement effects than individual genes (Dormatey et al., 2020; Haque et al., 2021). In soybean, this strategy is particularly suitable for improving disease and pest resistance, stress tolerance, and certain quality traits, which are determined by multiple functionally complementary major- or moderate-effect loci. Unlike traditional cumulative selection based on phenotypes, MAS can directly track multiple target loci in segregating generations, improving pyramiding efficiency and reducing misselection caused by environmental interference (Das et al., 2017). In disease-resistance breeding, pyramiding multiple R genes or major-effect QTLs, or combining major genes with minor-effect resistance loci, has been shown to enhance resistance spectrum and durability. This principle also applies to complex adaptive traits such as drought, salt, and waterlogging tolerance (Dormatey et al., 2020; Haque et al., 2021).

Marker-assisted backcrossing (MABC) is the core technical pathway for achieving gene pyramiding. Its basic framework includes foreground selection, recombinant selection, and background selection, aiming to restore the recurrent parent genome as quickly as possible while introducing target genes (Haque et al., 2021). In multiple crops, MABC can restore more than 95% of the recurrent parent genome within 3–4 backcrosses and successfully pyramid 4–10 resistance or tolerance loci, which is significantly faster than traditional backcrossing methods (Das et al., 2018; Pandit et al., 2021). With the introduction of high-density SNP chips, KASP, multiplex detection systems, and genomic selection models, breeders can now simultaneously track multiple loci, optimize population size, and improve pyramiding success rates, providing an actionable approach for modular improvement of complex target traits in soybean (Jarallah et al., 2025).

4.2 Breeding efficiency and limiting factors

Gene pyramiding through MAS improves traditional breeding efficiency. Its core advantage lies in the ability to directly identify target gene combinations at the seedling or early-generation stage, thereby reducing the number of materials carried into subsequent generations and saving field space, phenotyping costs, and breeding cycle time (Haque et al., 2021). In multiple crops, marker-assisted gene pyramiding can essentially restore elite genetic backgrounds within 2–4 backcrosses, whereas traditional backcrossing usually requires about six generations. It can also pyramid multiple resistance or tolerance loci, enhancing resistance levels and yield stability (Kumar et al., 2018; Haque et al., 2021). This means that breeders can not only simultaneously track multiple target loci through multi-marker detection, but also focus resources on the most promising recombinants using foreground and background selection, improving the accumulation efficiency of favorable genes in populations (Ramalingam et al., 2020).

However, multi-gene pyramiding is not without cost. As the number of target genes increases, the required population size rapidly expands; at the same time, gene linkage, QTL×QTL interactions, and donor fragment linkage drag increase screening difficulty and may weaken the expression of target genes in new genetic backgrounds (Das et al., 2017). Even if molecular detection confirms the target genotypes, rigorous background selection and multi-environment field trials are still needed to validate the combined performance of resistance, stress tolerance, yield, and adaptability.

4.3 Application of gene pyramiding in soybean breeding

In soybean breeding, MAS-based gene pyramiding has gradually shifted from theoretical strategy to practical application, with the most mature field still being disease-resistance breeding (Figure 3). Studies have used marker-assisted backcrossing to simultaneously introduce the *Phytophthora* root rot resistance gene *Rps2*, powdery mildew resistance gene *Rmd-c*, and effective nodulation-related genes into high-yielding variety backgrounds, resulting in new materials with multiple resistances and good agronomic performance. This demonstrates the feasibility of simultaneous multi-gene introgression in soybean (Ramalingam et al., 2020). The same concept also applies to the pyramiding of soybean cyst nematode resistance genes *Rhg1/Rhg4*, different *Rps* genes, and rust resistance genes, aiming to build broader-spectrum and more durable resistance systems within a single variety (Haque et al., 2021).

In terms of abiotic stress, although mature pyramiding cases reported in soybean are still fewer than those in crops such as rice, the relevant technical pathway has become relatively clear. As major-effect QTLs and candidate genes related to drought, salt, waterlogging, and heat tolerance continue to be validated, breeders can use MAS to integrate loci corresponding to different stress-resistance mechanisms—such as genes related to osmotic regulation, maintenance of ion homeostasis, and optimization of root architecture—into the same elite genetic background, thereby improving varietal stability and adaptability under complex environments (Dormatey et al., 2020; Pandit et al., 2021). In quality improvement, gene pyramiding also has clear potential. For example, joint selection of protein- and oil-related QTLs, fatty acid composition loci, and low-antinutritional-factor genes is expected to simultaneously improve nutritional value, processing quality, and marketability (Das et al., 2017; Zampieri et al., 2023).

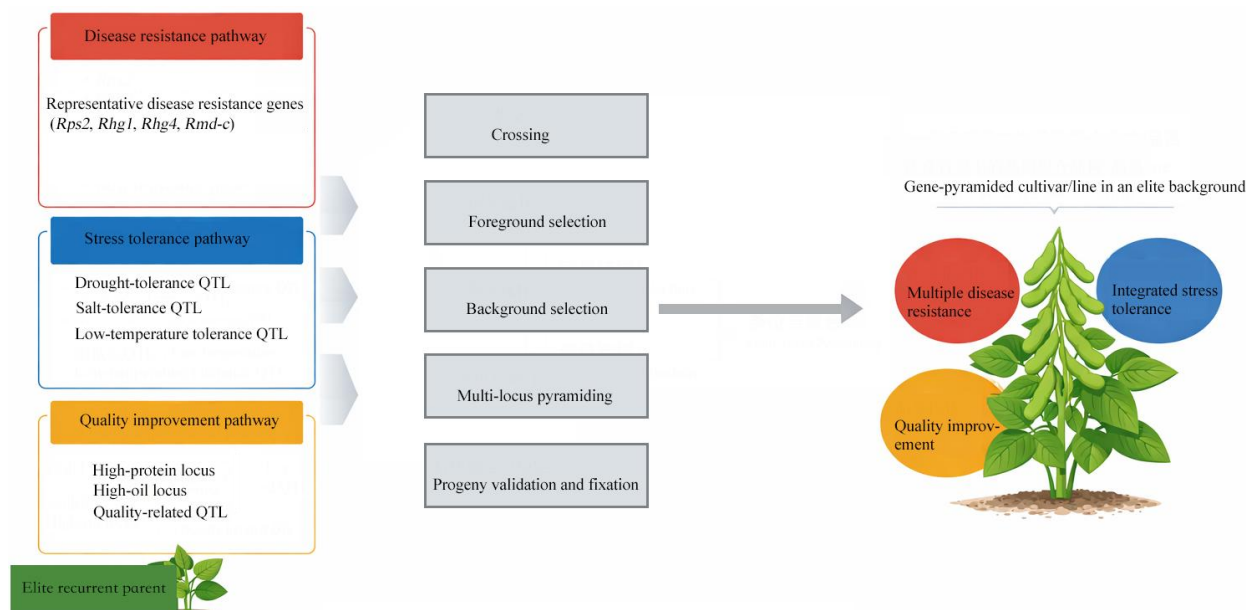


Figure 3 Representative applications of MAS-based gene pyramiding in soybean breeding

5 Limitations of MAS

5.1 Minor-effect QTLs

Although MAS has achieved significant results in the utilization of major genes and large-effect QTLs, its application is often clearly limited by the complex genetic architecture of minor-effect QTLs for typical quantitative traits such as yield, stress resistance, and certain quality traits. Such traits are usually jointly controlled by a large number of small-effect loci, with each individual locus explaining only a very low proportion of phenotypic variation. The remaining variation is also jointly influenced by undetected loci, environmental noise, and epistatic interactions. Therefore, relying only on a small number of markers makes it difficult to fully capture the complete genetic basis (Yáñez et al., 2023; Oh et al., 2025). When the target phenotype is jointly formed by multiple minor-effect QTLs through additive or interactive effects, the advantage of traditional MAS in “targeted selection of a few loci” is significantly weakened. This is also one of the important reasons why MAS is often inferior to genomic selection in the improvement of complex quantitative traits (Yáñez et al., 2023; Li and Lin, 2024).

Another key limitation lies in the poor environmental stability and transferability of minor-effect QTLs. Many minor-effect loci detected in specific populations and environments are often difficult to repeatedly validate under different genetic backgrounds, climatic conditions, or cultivation management practices, reflecting significant genotype $\times$ environment interactions and background-dependent marker–trait associations (Chang-Brahim et al., 2024; Li and Lin, 2024). Precise mapping of such loci usually requires large populations, high-density markers, and repeated validation across multiple environments in order to effectively distinguish true minor-effect QTLs from statistical false positives and reduce the risk of recombination between markers and causal variants (Song et al., 2023). In practical breeding, minor-effect QTLs are often difficult to stably convert into routine MAS tools in the same way as major genes.

5.2 Cost and operational challenges

Although MAS can theoretically significantly improve breeding efficiency, its routine promotion is still constrained by both cost and operational conditions, especially in resource-limited breeding programs. First, high-throughput genotyping, SNP chips, and sequencing-based detection platforms still involve relatively high costs when applied to large-scale populations, and often require dedicated instruments, reagents, and data processing software. As a result, although the testing cost per sample may decrease, the initial infrastructure investment and continuous operating expenses remain high (Song et al., 2023; Chang-Brahim et al., 2024). Even

when low-cost strategies such as pooled DNA, crude DNA extraction, or multiplex PCR are used to reduce the unit sample cost, laboratory platform construction, quality control, and professional personnel allocation still constitute important barriers (Ru et al., 2015).

MAS is not simply “molecular detection replacing phenotypic evaluation”. Instead, it requires the highly integrated implementation of marker development, DNA extraction, genotyping, data management, and conventional hybridization and selection procedures, which places high demands on a team’s capabilities in molecular biology, statistical analysis, and bioinformatics (Chang-Brahim et al., 2024). In practical operation, differences among laboratories in DNA quality, marker platforms, interpretation standards, and data management may all affect result consistency and technical reproducibility. Meanwhile, some breeding teams lack a clear cost–benefit evaluation framework and are uncertain about the breeding stage at which MAS should be introduced, making it difficult for molecular markers to be truly embedded into routine breeding decision-making processes (Ru et al., 2015). In developing countries or emerging breeding systems, insufficient funding, limited testing services, and pressure from short-term production goals further intensify this problem, resulting in an obviously uneven pattern of global MAS application.

5.3 Limitations of MAS in complex traits

The limitations of MAS are most prominent in the improvement of complex traits, especially in polygenic traits such as yield, adaptability, and comprehensive stress resistance. Such traits are usually determined by a large number of minor-effect loci and are simultaneously influenced by gene–environment interactions (G×E) and epistatic effects. Therefore, the phenotypic variation explained by a single or a few QTLs is very limited, making it difficult to accurately predict final performance (Yáñez et al., 2023). Taking soybean yield as an example, it is essentially the combined result of multiple component traits such as pod number, seed weight, branch number, and growth period. If only a few molecular markers are tracked, it is insufficient to capture the complete genetic basis, and the improvement magnitude may also be difficult to justify the cost and operational complexity of MAS implementation (Yáñez et al., 2023; Oh et al., 2025).

Marker–trait associations in complex traits often show clear environmental dependence: a QTL that is significant in one population or environment may have a weakened effect or even disappear under another genetic background, management condition, or climatic context, thereby reducing the stability and transferability of MAS results (Chang-Brahim et al., 2024; Li and Lin, 2024). Increasing numbers of studies advocate limiting MAS to major genes and large-effect QTLs, while assigning the improvement of highly polygenic traits more to genomic selection (GS), because GS can use whole-genome marker information to integrate a large number of minor-effect loci and their interaction effects (Yáñez et al., 2023; Kumar et al., 2025).

6 MAS in the Genomic Era

6.1 High-throughput genotyping technologies

With the rapid development of genomics, high-throughput genotyping technologies have significantly expanded the marker resources and application boundaries of MAS. Due to their wide distribution, high stability, and ease of automated detection, SNPs have become the core marker type in modern molecular breeding. Commercial SNP chips can typically detect tens of thousands to hundreds of thousands of loci simultaneously and have been widely used for QTL mapping, routine MAS, genomic selection (GS), and breeding quality control (Kumar et al., 2024). In soybean, high-density platforms such as SoySNP50K have been used for constructing genetic maps and screening key loci, providing a basis for high-precision MAS (Bhat et al., 2016).

The popularization of NGS has further promoted the development of sequencing-based genotyping (GBS). GBS can simultaneously discover and genotype thousands of SNPs at a relatively low cost through reduced-representation genome sequencing, combining high throughput with considerable flexibility. Even at lower sequencing depths, it can support genetic analysis of complex traits and prediction of breeding values (Bhat et al., 2016; Sinha et al., 2023). New platforms such as GBTS and mSNP liquid-phase chips provide layered schemes with approximately 1K to over 40K markers, allowing the same system to simultaneously serve

major-effect gene MAS and whole-genome prediction (Guo et al., 2019; 2021). Therefore, high-throughput genotyping technologies have enabled MAS to transition from “few-locus detection” to a new stage of “high-density, customizable, and integrable” applications.

6.2 Integration with genomic selection

Methodologically, the core difference between MAS and genomic selection (GS) lies in how molecular marker information is utilized. MAS primarily relies on a few discovered and validated markers that are tightly linked to major genes or large-effect QTLs, making it suitable for targeted selection of Mendelian or oligogenic traits such as disease resistance, maturity, and specific quality loci. In contrast, GS assumes that all genome-wide markers may be linked to causal variants and predicts genomic estimated breeding values (GEBVs) by simultaneously estimating all marker effects, making it more suitable for complex quantitative traits controlled by a large number of minor-effect loci (Bhat et al., 2016; Nanthini et al., 2025). In crops such as soybean, with the development of high-throughput SNP chips and GBS platforms, the predictive potential of GS for complex traits such as yield, stress tolerance, and comprehensive quality has continuously improved, while MAS still maintains an advantage in managing major-effect loci.

For highly polygenic complex traits, GS generally offers higher prediction accuracy and genetic gain per unit time than MAS, because it can integrate a large number of minor-effect loci across the genome and their combined effects without requiring individual markers to reach significance thresholds (Budhlakoti et al., 2022). However, when major-effect loci that explain a substantial proportion of phenotypic variation exist for the target trait, MAS still retains strong competitiveness. Therefore, the currently more practical strategy is not to replace MAS with GS, but to integrate the two: use MAS to introgress or fix key major-effect genes, such as disease-resistance genes, maturity genes, or important quality loci; simultaneously utilize GS to optimize the genetic background composed of numerous minor-effect loci, thus improving both Mendelian and quantitative components (Sinha et al., 2023; Kumar et al., 2024; Jarallah et al., 2025). This complementary approach of “precise control of major-effect loci + whole-genome background prediction” is becoming an important direction in soybean molecular breeding in the genomic era.

7 Future Prospects of MAS in Soybean Breeding

7.1 Improving accuracy and validation of molecular markers

The key to further enhancing the application value of MAS in soybean lies in continuously improving the accuracy, stability, and cross-population transferability of molecular markers. Currently, many markers are still based on “tight linkage with target genes or QTLs” rather than directly corresponding to causal variants, and their predictive ability may be reduced in different genetic backgrounds or ecological environments due to recombination or haplotype differences. This is particularly evident for traits regulated by multiple loci, such as seed weight, sucrose content, and seed quality (Bhat and Yu, 2021; Hasan et al., 2021). In the future, fine mapping, candidate gene analysis, and haplotype analysis should be more extensively employed to gradually upgrade traditional linked markers to functional markers or high-resolution targeted SNP panels, enabling markers to more directly reflect causal variants and thereby improving stability and accuracy in routine breeding (Yang et al., 2023).

The practical breeding value of molecular markers does not depend on “significance” but on “sufficient validation”. Future validation systems should emphasize cross-validation, independent population testing, and multi-environment trials to systematically evaluate marker stability across different germplasms and stress conditions. For example, SNPs associated with soybean pod shattering resistance can maintain over 90% prediction accuracy across different breeding stages and environments, indicating that rigorous validation is a prerequisite for markers to enter routine MAS pipelines (Kim et al., 2020). Only sufficiently validated markers have large-scale application value for critical decisions such as parental selection, hybrid design, and release of gene-edited materials. For complex traits, validated key markers can further be integrated with GS models to improve prediction efficiency and decision reliability (Xue et al., 2025).

7.2 Integrating MAS with multi-omics data

Future soybean MAS will no longer be limited to DNA-level linked markers, but will rely more on the coordinated integration of genomic, transcriptomic, proteomic, metabolomic, and high-throughput phenotypic data to systematically reveal the causal chains between “genotype–regulatory network–phenotype” (Hasan et al., 2021; Vargas-Almendra et al., 2024). For example, combining SNP information obtained from GWAS with transcriptomic expression patterns can more accurately distinguish truly functional candidate genes from markers that are merely in linkage. Further overlaying metabolomic data helps to pinpoint key pathways directly involved in seed component formation, stress responses, or developmental regulation, thereby improving the precision of functional marker development (Budhlakoti et al., 2022).

The value of multi-omics integration lies not only in improving marker development accuracy but also in enhancing the biological interpretability of MAS and its ability to improve complex traits. Studies have shown that incorporating a small number of metabolite markers obtained from metabolome association analysis into prediction models can increase the prediction accuracy of heterosis or complex traits by 4%-14%, sometimes even exceeding that of full genome–metabolome models (Xu et al., 2025). Applying similar strategies to soybean allows breeders to prioritize markers from transcripts, proteins, or metabolites with clear functional links to sucrose, isoflavones, protein, oil, or stress responses, making MAS not just “tracking loci” but “fixing favorable alleles within regulatory networks” (Riaz et al., 2023; Xue et al., 2025). In the future, multi-omics-driven MAS can also synergize with GS and gene editing to provide more interpretable and precise molecular breeding strategies for complex traits.

7.3 Developing climate-adapted soybean varieties

Climate change continues to intensify the combined stresses of high temperature, drought, flooding, and emerging pests and diseases on soybean production. Therefore, developing climate-adapted varieties with high yield, stable yield, stress resistance, and superior quality has become one of the core goals of future molecular breeding in soybean (Budhlakoti et al., 2022; Vargas-Almendra et al., 2024). In this process, MAS still plays an irreplaceable role, particularly suitable for tracking and pyramiding major disease-resistance genes, maturity-related genes, and certain stable stress-resistance loci. For highly polygenic traits such as drought tolerance, heat tolerance, and broad adaptability, MAS is best combined with GS to simultaneously capture the contributions of numerous minor-effect loci to complex stress responses (Budhlakoti et al., 2022). Therefore, future climate-adapted soybean breeding should not focus solely on single-stress tolerance but should prioritize fixing key adaptive alleles through MAS, and then optimize the whole-genome background using GS to maintain yield and quality stability under complex environments.

The future climate-adapted soybean breeding system is likely to adopt a comprehensive “MAS + GS + gene editing + rapid breeding” model: MAS is used to identify and fix key alleles, GS predicts combined breeding values under different environments, CRISPR/Cas is used to precisely introduce superior allelic variants when natural variation is insufficient, and rapid breeding shortens generation time to accelerate fixation of target genotypes (Fang et al., 2021; Vargas-Almendra et al., 2024). Studies have shown that optimizing hybrid combinations using genomic prediction can significantly improve the efficiency of soybean genetic improvement. This strategy can also be extended to prioritize the selection of hybrid combinations that combine stress resistance, disease resistance, suitable maturity, and superior quality (Miller et al., 2023). Therefore, MAS in the future will not be applied in isolation but will serve as a “key-locus anchoring tool” in climate-adapted breeding, embedded within a more systematic molecular design breeding framework to support global food and feed security.

8 Concluding Remarks

Marker-assisted selection (MAS) has become an important technical foundation of modern soybean molecular breeding and has profoundly changed the way genetic variation is discovered, tracked, and utilized. With the development of molecular marker systems from RFLP and SSR to high-density SNP chips and NGS-based detection platforms, breeders are able to more efficiently associate genomic regions with disease resistance, adaptability, quality, and some yield-related traits. In soybean, MAS is particularly effective for traits controlled

by single genes or a small number of major-effect genes. It has achieved stable results in resistance to soybean cyst nematode, resistance to *Phytophthora* root rot, regulation of maturity, and improvement of certain seed quality traits, and has significantly shortened the breeding cycle through marker-assisted backcrossing and gene pyramiding.

However, the advantages of MAS are mainly concentrated in the management of major-effect loci, and clear limitations remain in the improvement of complex quantitative traits. Traits such as yield stability, climate adaptability, and multiple-stress tolerance are usually jointly affected by numerous minor-effect QTLs, gene–environment interactions, and genetic background effects. A small number of markers are difficult to fully explain their phenotypic variation, and therefore their predictive ability is usually weaker than that of genomic selection (GS). MAS is also constrained by the accuracy of phenotypic evaluation, marker stability across populations, environmental dependence of QTLs, and continuous genotyping costs. These problems are particularly prominent in resource-limited breeding systems.

In the future, MAS will not be replaced, but will be repositioned within an integrated genomic breeding framework. A more efficient strategy is to use MAS to precisely track key disease-resistance genes, major adaptive loci, and functional markers, while using GS to optimize polygenic backgrounds. At the same time, multi-omics analysis, high-throughput phenotyping, and artificial intelligence prediction should be integrated to improve the efficiency of candidate locus discovery and cross-environment prediction ability. On this basis, gene-editing technologies such as CRISPR/Cas will enable breeding to gradually move from “indirect selection based on linked markers” toward “direct modification or regulation of causal alleles.”

The development trajectory of MAS in soybean shows that it has evolved from a single molecular tool into a key component of modern precision breeding systems. As long as molecular markers are fully validated and applied synergistically with GS, gene editing, and multi-omics technologies, MAS will remain an important bridge connecting key genes with breeding practice, and will continue to play a central role in developing new soybean varieties with high yield, superior quality, stress resistance, and adaptation to climate change.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Amangeldiyeva A., Yezhebayeva R., Mazkirat S., Didorenko S., Bastaubayeva S., Maikotov B., Kassenov R., Jenisbayeva A., and Shavrukov Y., 2025, Yield and yield component trait analysis with DArT genotyping for GWAS in soybean grown in drought conditions of Kazakhstan, *Frontiers in Plant Science*, 16: 1674201.
<https://doi.org/10.3389/fpls.2025.1674201>
- Bhat J.A., and Yu D., 2021, High-throughput NGS-based genotyping and phenotyping: role in genomics-assisted breeding for soybean improvement, *Legume Science*, 3(3): e81.
<https://doi.org/10.1002/leg3.81>
- Bhat J.A., Ali S., Salgotra R.K., Mir Z.A., Dutta S., Jadon V., Tyagi A., Mushtaq M., Jain N., Singh P., Singh G., and Prabhu K., 2016, Genomic selection in the era of next generation sequencing for complex traits in plant breeding, *Frontiers in Genetics*, 7: 221.
<https://doi.org/10.3389/fgene.2016.00221>
- Budhlakoti N., Kushwaha A.K., Rai A., Chaturvedi K.K., Kumar A., Pradhan A.K., Kumar U., Kumar R., Juliana P., Mishra D., and Kumar S., 2022, Genomic selection: a tool for accelerating the efficiency of molecular breeding for development of climate-resilient crops, *Frontiers in Genetics*, 13: 832153.
<https://doi.org/10.3389/fgene.2022.832153>
- Chang-Brahim I., Koppensteiner L.J., Beltrame L., Bodner G., Saranti A., Salzinger J., Fanta-Jende P., Sulzbachner C., Bruckmüller F., Trognitz F., Samad-Zamini M., Zechner E., Holzinger A., and Molin E.M., 2024, Reviewing the essential roles of remote phenotyping, GWAS and explainable AI in practical marker-assisted selection for drought-tolerant winter wheat breeding, *Frontiers in Plant Science*, 15: 1319938.
<https://doi.org/10.3389/fpls.2024.1319938>

- Das G., Rao G.J., Varier M., Prakash A., and Prasad D., 2018, Improved Tapaswini having four BB resistance genes pyramided with six genes/QTLs, resistance/tolerance to biotic and abiotic stresses in rice, *Scientific Reports*, 8(1): 2413.
<https://doi.org/10.1038/s41598-018-20495-x>
- Das G., Patra J.K., and Baek K.H., 2017, Insight into MAS: a molecular tool for development of stress resistant and quality of rice through gene stacking, *Frontiers in Plant Science*, 8: 985.
<https://doi.org/10.3389/fpls.2017.00985>
- Dormatey R., Sun C., Ali K., Coulter J.A., Bi Z., and Bai J., 2020, Gene pyramiding for sustainable crop improvement against biotic and abiotic stresses, *Agronomy*, 10(9): 1255.
<https://doi.org/10.20944/preprints202008.0088.v1>
- Fang Y., Wang L., Sapay E., Fu S., Wu T., Zeng H., Sun X., Qian S., Khan M., Yuan S., Wu C., Hou W., Sun S., and Han T., 2021, Speed-breeding system in soybean: integrating off-site generation advancement, fresh seeding, and marker-assisted selection, *Frontiers in Plant Science*, 12: 717077.
<https://doi.org/10.3389/fpls.2021.717077>
- Gai Y., Liu S., Zhang Z., Wei J., Wang H., Liu L., Bai Q., Qin Q., Zhao C., Zhang S., Xiang N., and Zhang X., 2025, Integrative approaches to soybean resilience, productivity, and utility: a review of genomics, computational modeling, and economic viability, *Plants*, 14(5): 671.
<https://doi.org/10.3390/plants14050671>
- Guo Z., Wang H., Tao J., Ren Y., Xu C., Wu K., Zou C., Zhang J., and Xu Y., 2019, Development of multiple SNP marker panels affordable to breeders through genotyping by target sequencing (GBTS) in maize, *Molecular Breeding*, 39(3): 37.
<https://doi.org/10.1007/s11032-019-0940-4>
- Guo Z., Yang Q., Huang F., Zheng H., Sang Z., Xu Y., Zhang C., Wu K., Tao J., Prasanna B., Olsen M., Wang Y., Zhang J., and Xu Y., 2021, Development of high-resolution multiple-SNP arrays for genetic analyses and molecular breeding through genotyping by target sequencing and liquid chip, *Plant Communications*, 2(6): 100230.
<https://doi.org/10.1016/j.xplc.2021.100230>
- Haque M.A., Rafii M.Y., Yusoff M.M., Ali N.S., Yusuff O., Datta D.R., Anisuzzaman M., and Ikbai M.F., 2021, Recent advances in rice varietal development for durable resistance to biotic and abiotic stresses through marker-assisted gene pyramiding, *Sustainability*, 13(19): 10806.
<https://doi.org/10.3390/su131910806>
- Hasan N., Choudhary S., Naaz N., Sharma N., and Laskar R.A., 2021, Recent advancements in molecular marker-assisted selection and applications in plant breeding programmes, *Journal of Genetic Engineering and Biotechnology*, 19(1): 128.
<https://doi.org/10.1186/s43141-021-00231-1>
- Hassan M.A., Dahu N., Hongning T., Qian Z., Yueming Y., Yiru L., and Shimei W., 2023, Drought stress in rice: morpho-physiological and molecular responses and marker-assisted breeding, *Frontiers in Plant Science*, 14: 1215371.
<https://doi.org/10.3389/fpls.2023.1215371>
- Huang J., Q., Cai Z., Xia Q., Li S., Jia J., Chu L., Lian T., Nian H., and Cheng Y., 2020, Identification and mapping of stable QTLs for seed oil and protein content in soybean [*Glycine max* (L.) Merr.], *Journal of Agricultural and Food Chemistry*, 68(23): 6448-6460.
<https://doi.org/10.1021/acs.jafc.0c01271>
- Huang S., Xia Y., Yang J., Si Y., Chen X., Zhang H., Liu T., Zheng W., Chen X., Zhao Z., Zheng X., Lu Q., Li S., and Xiang F., 2025, A coding SNP in GmPM30 enhances soybean salinity tolerance and yield through the GmLEA1-GmPM30-GmLEC1 module, *Advanced Science*, 12(44): e09391.
<https://doi.org/10.1002/advs.202509391>
- Jarallah M.H., Mouhsan Z.M., and Alamry A.T., 2025, Integration of genetic tools: strategies for combining traditional and modern breeding to combat plant diseases, *European Journal of Ecology, Biology and Agriculture*, 2(4): 79-91.
[https://doi.org/10.59324/ejeba.2025.2\(4\).07](https://doi.org/10.59324/ejeba.2025.2(4).07)
- Jin H., Yang X., Zhao H., Song X., Tsvetkov Y., Wu Y., Gao Q., Zhang R., and Zhang J., 2023, Genetic analysis of protein content and oil content in soybean by genome-wide association study, *Frontiers in Plant Science*, 14: 1182771.
<https://doi.org/10.3389/fpls.2023.1182771>
- Kim D.G., Lyu J.I., Lim Y.J., Kim J.M., Hung N.N., Eom S.H., Kim S., Kim J., Bae C., and Kwon S.J., 2021, Differential gene expression associated with altered isoflavone and fatty acid contents in soybean mutant diversity pool, *Plants*, 10(6): 1037.
<https://doi.org/10.3390/plants10061037>
- Kim J.M., Kim K.H., Jung J., Kang B.K., Lee J., Ha B.K., and Kang S., 2020, Validation of marker-assisted selection in soybean breeding program for pod shattering resistance, *Euphytica*, 216(11): 166.
<https://doi.org/10.1007/s10681-020-02703-w>
- Kumar A., Sandhu N., Dixit S., Yadav S., Swamy B.P.M., and Shamsudin N.A.A., 2018, Marker-assisted selection strategy to pyramid two or more QTLs for quantitative trait-grain yield under drought, *Rice*, 11(1): 35.
<https://doi.org/10.1186/s12284-018-0227-0>
- Kumar B., Yankanchi S., Singh R., P., Sarkar D., Kumar P., Kumar K., Choudhary M., Jat B., and Jat H.S., 2025, Dissecting the genetic architecture of polygenic nutritional traits in maize through meta-QTL analysis, *Food Chemistry: Molecular Sciences*, 10: 100256.
<https://doi.org/10.1016/j.fochms.2025.100256>

- Kumar R., Das S.P., Choudhury B.U., Kumar A., Prakash N.R., Verma R., Chakraborti M., Devi A., Bhattacharjee B., Das R., Das B., Devi H., Das B., Rawat S., and Mishra V.K., 2024, Advances in genomic tools for plant breeding: harnessing DNA molecular markers, genomic selection, and genome editing, *Biological Research*, 57(1): 80.
<https://doi.org/10.1186/s40659-024-00562-6>
- Kumar V., Goyal V., Mandlik R., Kumawat S., Sudhakaran S., Padalkar G., Rana N., Deshmukh R., Roy J., Sharma T., and Sonah H., 2022, Pinpointing genomic regions and candidate genes associated with seed oil and protein content in soybean through an integrative transcriptomic and QTL meta-analysis, *Cells*, 12(1): 97.
<https://doi.org/10.3390/cells12010097>
- Lee S., Van K., Sung M., Nelson R., LaMantia J., McHale L.K., and Mian M.R., 2019, Genome-wide association study of seed protein, oil and amino acid contents in soybean from maturity groups I to IV, *Theoretical and Applied Genetics*, 132(6): 1639-1659.
<https://doi.org/10.1007/s00122-019-03304-5>
- Li B., Fan S., Yu F., Chen Y., Zhang S., Han F., Yan S., Wang L., and Sun J., 2017, High-resolution mapping of QTL for fatty acid composition in soybean using specific-locus amplified fragment sequencing, *Theoretical and Applied Genetics*, 130(7): 1467-1479.
<https://doi.org/10.1007/s00122-017-2902-8>
- Li J., and Lin X., 2024, Analyzing the impact of marker-assisted selection on livestock productivity and genetic diversity, *Animal Molecular Breeding*, 14.
<https://doi.org/10.5376/amb.2024.14.0014>
- Li S., Guo C., Feng X., Wang J., Pan W., Xu C., Wei S., Han X., Yang M., Chen Q., Wang J., Hu L., and Qi Z., 2024, Development and validation of competitive allele-specific polymerase chain reaction markers for seed protein content in soybean, *Plants*, 13(24): 3485.
<https://doi.org/10.3390/plants13243485>
- Lin F., Chhakekar S.S., Vieira C.C., Da Silva M.P., Rojas A., Lee D., Liu N., Pardo E., Lee Y., Dong Z., Pinheiro J., Ploper L., Rupe J., Chen P., Wang D., and Nguyen H., 2022, Breeding for disease resistance in soybean: a global perspective, *Theoretical and Applied Genetics*, 135(11): 3773-3872.
<https://doi.org/10.1007/s00122-022-04101-3>
- Ma Y., Reif J., Jiang Y., Wen Z., Wang D., Liu Z., Guo Y., Wei S., Wang S., Yang C., Wang H., Yang C., Lu W., Xu R., Zhou R., Wang R., Sun Z., Chen H., Zhang W., Wu J., Hu G., Liu C., Luan X., Fu Y., Guo T., Han T., Zhang M., Sun B., Zhang L., Chen W., Wu C., Sun S., Yuan B., Zhou X., Han D., Yan H., Li W., and Qiu L., 2016, Potential of marker selection to increase prediction accuracy of genomic selection in soybean (*Glycine max* L.), *Molecular Breeding*, 36(8): 113.
<https://doi.org/10.1007/s11032-016-0504-9>
- Manghwar H., Zaman W., Chugh V., Kaur D., Purwar S., Kaushik P., Sharma V., Kumar H., Rai A., Singh C., and Dubey R., 2022, Applications of molecular markers for developing abiotic-stress-resilient oilseed crops, *Life*, 13(1): 88.
<https://doi.org/10.3390/life13010088>
- Miller M.J., Song Q., and Li Z., 2023, Genomic selection of soybean (*Glycine max*) for genetic improvement of yield and seed composition in a breeding context, *The Plant Genome*, 16(4): e20384.
<https://doi.org/10.1002/tpg2.20384>
- Nanthini B., Venkatachalam S.R., Arutchenthil P., Natarajan S.K., and Jaya Prabhavathi S., 2025, Review on genomic selection in plant breeding, *Plant Science Today*, 12(3): 2348-1900.
<https://doi.org/10.14719/pst.8556>
- Oh H., Mengist M., G., Giongo L., Pottorff M., Spencer J., Perkins-Veazie P., and Iorizzo M., 2025, Unraveling the genetic architecture of blueberry fruit quality traits: major loci control organic acid content while more complex genetic mechanisms control texture and sugar content, *BMC Plant Biology*, 25(1): 36.
<https://doi.org/10.1186/s12870-025-06061-4>
- Pandit E., Pawar S., Barik S.R., Mohanty S.P., Meher J., and Pradhan S.K., 2021, Marker-assisted backcross breeding for improvement of submergence tolerance and grain yield in the popular rice variety 'Maudamani', *Agronomy*, 11(7): 1263.
<https://doi.org/10.3390/agronomy11071263>
- Patel J., Patel S., Cook L., Fallen B.D., and Koebernick J., 2025, Soybean genome-wide association study of seed weight, protein, and oil content in the southeastern USA, *Molecular Genetics and Genomics*, 300(1): 43.
<https://doi.org/10.1007/s00438-025-02228-8>
- Podzorova T., Zatybekov A., Didorenko S., and Abugalieva S., 2022, Genetic variation of soybean collection based on microsatellite DNA markers related to plant height, *Eurasian Journal of Applied Biotechnology*, (2): 3-12.
<https://doi.org/10.11134/btp.2.2022.1>
- Qu S., Hu S., Song G., Sun H., Liu F., Zhang M., Zhan Y., Li Y., Teng W., Li H., Zhao X., and Han Y., 2025, Genome-wide association study and molecular marker development for resistance to soybean cyst nematode in soybean, *The Plant Genome*, 18(3): e70083.
<https://doi.org/10.1002/tpg2.70083>
- Ramalingam J., Alagarasan G., Savitha P., Lydia K., Pothiraj G., Vijayakumar E., Sudhagar R., Singh A., Vedna K., and Vanniarajan C., 2020, Improved host-plant resistance to Phytophthora rot and powdery mildew in soybean (*Glycine max* (L.) Merr.), *Scientific Reports*, 10(1): 13928.
<https://doi.org/10.1038/s41598-020-70702-x>

- Ramayya P., Vinukonda V., Singh U., Alam S., Venkateshwarlu C., Vipparla A., Dixit S., Yadav S., Abbai R., Badri J., T R., Padmakumari A., Singh V., and Kumar A., 2021, Marker-assisted forward and backcross breeding for improvement of elite Indian rice variety Naveen for multiple biotic and abiotic stress tolerance, PLoS One, 16(9): e0256721.
<https://doi.org/10.1371/journal.pone.0256721>
- Ravelombola W., Qin J., Shi A., Song Q., Yuan J., Wang F., Chen P., Yan L., Feng Y., Zhao T., Meng Y., Guan K., Yang C., and Zhang M., 2021, Genome-wide association study and genomic selection for yield and related traits in soybean, PLoS One, 16(8): e0255761.
<https://doi.org/10.1371/journal.pone.0255761>
- Riaz A., Raza Q., Kumar A., Dean D., Chiwina K., Phiri T., Thomas J., and Shi A., 2023, GWAS and genomic selection for marker-assisted development of sucrose enriched soybean cultivars, Euphytica, 219(9): 97.
<https://doi.org/10.1007/s10681-023-03224-y>
- Ru S., Main D., Evans K., and Peace C., 2015, Current applications, challenges, and perspectives of marker-assisted seedling selection in Rosaceae tree fruit breeding, Tree Genetics and Genomes, 11(1): 8.
<https://doi.org/10.1007/s11295-015-0834-5>
- Shi A., Gepts P., Song Q., Xiong H., Michaels T.E., and Chen S., 2021, Genome-wide association study and genomic prediction for soybean cyst nematode resistance in USDA common bean (*Phaseolus vulgaris*) core collection, Frontiers in Plant Science, 12: 624156.
<https://doi.org/10.3389/fpls.2021.624156>
- Sinha D., Maurya A.K., Abdi G., Majeed M., Agarwal R., Mukherjee R., Ganguly S., Aziz R., Bhatia M., Majgaonkar A., Seal S., Das M., Banerjee S., Chowdhury S., Adeyemi S., and Chen J.T., 2023, Integrated genomic selection for accelerating breeding programs of climate-smart cereals, Genes, 14(7): 1484.
<https://doi.org/10.3390/genes14071484>
- Song L., Wang R., Yang X., Zhang A., and Liu D., 2023, Molecular markers and their applications in marker-assisted selection (MAS) in bread wheat (*Triticum aestivum* L.), Agriculture, 13(3): 642.
<https://doi.org/10.3390/agriculture13030642>
- Sun B., Guo R., Liu Z., Shi X., Yang Q., Shi J., Zhang M., Yang C., Zhao S., Zhang J., He J., Zhang J., Su J., Song Q., and Yan L., 2022, Genetic variation and marker-trait association affect the genomic selection prediction accuracy of soybean protein and oil content, Frontiers in Plant Science, 13: 1064623.
<https://doi.org/10.3389/fpls.2022.1064623>
- Vargas-Almendra A., Ruiz-Medrano R., Núñez-Muñoz L.A., Ramírez-Pool J.A., Calderón-Pérez B., and Xoconostle-Cázares B., 2024, Advances in soybean genetic improvement, Plants, 13(21): 3073.
<https://doi.org/10.3390/plants13213073>
- Wang X., Qi Y., Sun G., Zhang S., Li W., and Wang Y., 2024, Improving soybean breeding efficiency using marker-assisted selection, Molecular Plant Breeding, 15: 1-9.
<https://doi.org/10.5376/mpb.2024.15.0025>
- Wang X., Zhang M., Li F., Liu X., Zhang C., Zhang F., Zhao K., Yuan R., Lamlo S., Ren H., Qiu H., and Zhang B., 2025, Genome-wide association study reveals key genetic loci controlling oil content in soybean seeds, Agronomy, 15(8): 1889.
<https://doi.org/10.3390/agronomy15081889>
- Xu Y., Yang W., Qiu J., Zhou K., Yu G., Zhang Y., Wang X., Jiao Y., Wang X., Hu S., Zhang X., Li P., Lu Y., Chen R., Tao T., Yang Z., Xu Y., and Xu C., 2025, Metabolic marker-assisted genomic prediction improves hybrid breeding, Plant Communications, 6(3): 101199.
<https://doi.org/10.1016/j.xplc.2024.101199>
- Xu Y., Zhang X., Li H., Zheng H., Zhang J., Olsen M., Varshney R., Prasanna B., and Qian Q., 2022, Smart breeding driven by big data, artificial intelligence, and integrated genomic-environmental prediction, Molecular Plant, 15(11): 1664-1695.
<https://doi.org/10.1016/j.molp.2022.09.001>
- Xue Y., Tang X., Zhu X., Zhang R., Yao Y., Cao D., He W., Liu Q., Luan X., Shu Y., and Liu X., 2025, Leveraging GWAS-identified markers in combination with Bayesian and machine learning models to improve genomic selection in soybean, International Journal of Molecular Sciences, 26(19): 9586.
<https://doi.org/10.3390/ijms26199586>
- Yang Q., Zhang J., Shi X., Chen L., Qin J., Zhang M., Yang C., Song Q., and Yan L., 2023, Development of SNP marker panels for genotyping by target sequencing (GBTS) and its application in soybean, Molecular Breeding, 43(4): 26.
<https://doi.org/10.1007/s11032-023-01372-6>
- Yao D., Zhao Q., Li T., Wang J., Wang L., Liu Y., Hao W., and Liu H., 2022, Genetic analysis and quantitative trait locus mapping using the major gene plus polygene model for soybean [*Glycine max* (L.) Merr.] main quality trait, Legume Research - An International Journal, 45(1): 18-24.
<https://doi.org/10.18805/lrf-705>
- Yerzhebayeva R., Didorenko S., Amangeldiyeva A., Daniyarova A., Mazkirat S., Zinchenko A., and Shavruk Y., 2023, Marker-assisted selection for early maturing E loci in soybean yielded prospective breeding lines for high latitudes of Northern Kazakhstan, Biomolecules, 13(7): 1146.
<https://doi.org/10.3390/biom13071146>
- Yáñez J.M., Barria A., López M.E., Moen T., García B.F., Yoshida G.M., and Xu P., 2023, Genome-wide association and genomic selection in aquaculture, Reviews in Aquaculture, 15(2): 645-675.
<https://doi.org/10.1111/raq.12750>

- Zampieri E., Volante A., Marè C., Orasen G., Desiderio F., Biselli C., Canella M., Carmagnola L., Milazzo J., Adreit H., Tharreau D., Poncelet N., Vaccino P., and Valè G., 2023, Marker-assisted pyramiding of blast-resistance genes in a japonica elite rice cultivar through forward and background selection, *Plants*, 12(4): 757.
<https://doi.org/10.3390/plants12040757>
- Zhang H., Goettel W., Song Q., Jiang H., Hu Z., Wang M.L., and An Y.Q.C., 2020, Selection of *GmSWEET39* for oil and protein improvement in soybean, *PLoS Genetics*, 16(11): e1009114.
<https://doi.org/10.1371/journal.pgen.1009114>
- Zhang J., Song Q., Cregan P.B., and Jiang G.L., 2016, Genome-wide association study, genomic prediction and marker-assisted selection for seed weight in soybean (*Glycine max*), *Theoretical and Applied Genetics*, 129(1): 117-130.
<https://doi.org/10.1007/s00122-015-2614-x>
- Zhao K., Hong H., Liu X., Wang X., Zhang C., Zhang F., Yuan R., Lamlo S., Ren H., and Zhang B., 2025, Multi-omics integration reveals heavy ion-induced enhancement of soybean isoflavone biosynthesis, *Physiologia Plantarum*, 177(5): e70508.
<https://doi.org/10.1111/ppl.70508>

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Research Article

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Effect of Different Concentrations of Gibberellic Acid (GA₃) and Naphthalene Acetic Acid (NAA) on Growth and Seed Yield of Cabbage at Marpha, MustangSharmila Tiwari¹ ✉, Surendra Khadka¹, Binaya Babu Koirala², Padma Nath Atreya², Arjun Subedi³, Sudip Tiwari¹, Nitika Pandey¹, Amit Chhetri¹¹ Faculty of Agriculture, Agriculture and Forestry University, Rampur, Chitwan, 44209, Nepal² Temperate Horticulture Development Center, Marpha, Mustang, 33100, Nepal³ Department of Horticulture, Agriculture and Forestry University, Rampur, Chitwan, 44209, Nepal✉ Corresponding author: sharmilatiwari37@gmail.comInternational Journal of Horticulture, 2026, Vol.16, No.3 doi: [10.5376/ijh.2026.16.0015](https://doi.org/10.5376/ijh.2026.16.0015)

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Abstract The experiment was carried out at Marpha, Mustang in order to determine the effect of different concentrations of plant growth regulators: Gibberellic acid (GA₃) and naphthalene acetic acid (NAA) on growth and seed yield of cabbage from February to July 2024. The experiment was laid out in one factor randomized complete block design (RCBD) with seven treatments. The treatments consist of application of different concentrations of GA₃ and NAA namely: T₁: Control (distilled water spray), T₂: GA₃-50 ppm, T₃: GA₃-75 ppm, T₄: GA₃-100 ppm, T₅: NAA-50 ppm, T₆: NAA-75 ppm and T₇: NAA-100 ppm. Each treatment was replicated 3 times. Thus, there were 21 plots consisting of 2 sample plants in each plot. So, there were total of 42 plants. Different growth parameters like peduncle height, number of leaves, number of branches, canopy cover and yield parameters like number of inflorescences, number of pods per inflorescence, number of seeds per pod, Thousand Grain Weight (TGW), seed yield per plant were assessed. The solution for spray was made using standard procedures. Application of the plant growth regulators was done twice; the first application was done at the time of head initiation and second application was done at 50% flowering. The data was first entered in MS excel and R-Stat was used for further analysis of the parameters. The application of GA₃ at 50 ppm (2.91 t/ha) was found most effective for seed yield than other treatments. The control treatment was found least effective in all parameters. Similarly, other growth and yield parameters like peduncle height, leaf number, number of pods per inflorescence and Thousand Grain Weight (TGW) were found to be highest by the application of GA₃ at 50 ppm. Hence the results revealed that the different concentrations of GA₃ and NAA significantly influenced seed yield of cabbage along with growth parameters.

Keywords Plant growth regulators; GA₃; NAA; Cabbage; Seed yield; Growth**1 Introduction**

Nepal is a small landlocked mountainous country bordered by India in south, east and west and China in north. Agriculture is chiefly recognized as the mainstream economic sector in Nepal for the overall development and remained as a major concern to the government, business and to the general people in large (Pokhrel and Rijal, 2017). Agriculture employs 65.7% of the labor force in Nepal. In Nepal, 3,091,000 hectares of land area is under cultivation and 1,030,000 hectares of cultivable land is still not cultivated (MoALD, 2018). The contribution of agriculture sector in natural GDP is 31.23%, where horticulture sub-sector has the most significant role, sharing 21.42% in AGDP of the country (MoALD, 2016).

Cabbage (*Brassica oleracea* var. *capitata*) is one of the most consumed and most important leafy vegetables worldwide due to its high nutritional value (Sawant et al., 2010; Shrestha, 2019). It is therefore necessary to improve the seeds of cabbage for more production. This is a plant that grows in certain regions of the temperate zone and is cultivated every two years (Ahmed et al., 2019). However, its cultivation is equally successful in the tropical and sub-tropical regions (Devi et al., 2017). It is used as vegetables in curries, salad, and pickling. It is taken alone or in combination with potatoes for purposes of preparing vegetables (Singh, 2015). As per studies, it

was found that 100 g of the green edible portion of the cabbage is present with 92 %water, 18 mg sodium, 170 mg potassium, 1.28 g protein, 5.8 g carbohydrate, 4 % calcium, and 2 % mg iron (Dev et al., 2020). It is also rich in indole-3-carbinol which helps in improving the capability of DNA repair in cells and seems to hinder the formation of cancer cells (Moniruzzaman et al., 2019). The seed production in cabbage can be done by seed to seed and head to seed method. In head to seed method, head intact method is especially practiced where a cross cut is made to facilitate the emergence of the flower stalk (Singh et al., 2018). Despite its importance, cabbage seed production occupies a relatively small portion of the vegetable seed importance sector. It accounts for about 0.5% of the vegetable seed-producing land (Aryal et al., 2022). Seed yield and quality are critical factors influencing cabbage productivity. However, cabbage seed production is often constrained by climatic conditions, particularly in cold and high-altitude environments where low temperatures and short growing seasons can adversely affect flowering, seed set and maturation. The application of plant growth regulators has therefore been studied as a method of enhancing cabbage and reproductive performance.

Gibberellic acid (GA₃) and naphthalene acetic acid (NAA) are widely used plant growth hormones which exhibited beneficial effect in several crops such as cell elongation and floral induction (Chaurasiy et al., 2014). Similarly, application of plant growth regulator is also better to enhance the yield of vegetable without compromising with their quality (Singh and Verma, 2021). Previous studies have reported that GA₃ application can enhance plant height, leaf number, flowering and seed yield in cabbage and other Brassicaceae crops (Moniruzzaman et al., 2019; Dev et al., 2020). Similarly, NAA has been shown to enhance flower retention, pod development and seed maturation by influencing auxin-related physiological mechanisms. However, the majority of these investigations have been carried out in lowland or moderate climatic conditions.

Systemic studies evaluating the combined and comparative effects of GA₃ and NAA on cabbage seed production under high-altitude, cold climate conditions remain limited. Specifically, data regarding ideal hormone levels for improving seed yield in areas like Mustang, Nepal is limited. Therefore, this study was conducted to evaluate the effects of different concentrations of GA₃ and NAA on the growth and seed yield of cabbage in high altitude environments, with the goal of producing location-specific recommendations for cabbage seed production in colder areas.

2 Materials and Methods

2.1 Experimental site and climate

The experiment was conducted at Temperate Horticulture Development Center (THDC) located at Gharapjhong Rural Municipality-2, Marpha, Mustang district, coordinated at 28 °20' to 29 °05' N and 83 °30' to 84 °15' E with an altitude of 2,650 masl. The area is characterized by a cold, high altitude climate with cool summers and cold winters. The average annual minimum and maximum temperature range reported during the research period were 4.9 °C-20.7 °C. The average annual rainfall of the study site was recorded to be about 36.875 mm. The soil in the experimental area was sandy loam to sandy in texture, well-drained and was prepared by ploughing and leveling before transplanting.

2.2 Plant material and experimental design

The experiment was conducted using cabbage (*Brassica oleraceae* var. *capitata*) plants of Copenhagen market variety. The head of the matured cabbage was transplanted at the first week of Bhadra. Transplanting was done at a spacing of 60 × 75 cm and plot size was maintained 2.40 × 3.00 m. The experiment was laid out in a single-factor Randomized Complete Block Design (RCBD) with 7 treatments and 3 replications. The treatments namely T₁, T₂, T₃, T₄, T₅, T₆ and T₇ consisted of different concentrations of GA₃ and NAA including a control which is shown in (Table 1).

Table 1 List of treatments and application doses

Treatments	Concentration (ppm)
T ₁	Control (Spraying distilled water)
T ₂	GA ₃ -50 ppm
T ₃	GA ₃ -75 ppm
T ₄	GA ₃ -100 ppm
T ₅	NAA-50 ppm
T ₆	NAA-75 ppm
T ₇	NAA-100 ppm

2.3 Cultural practices

Standard agronomic practices were followed throughout the experimental period. Land preparation involved deep ploughing followed by harrowing to make soil free from large soil clods and weeds prior to transplanting. Seedlings of uniform size and age were transplanted carefully. Fertilizers were applied according to recommended doses, with basal and topdressing applications. Irrigation was provided immediately after transplanting to maintain adequate soil moisture, then it was given at 7-8 days interval. Weeding and plant protection measures were carried out uniformly across all plots to minimize biotic stress.

2.4 Data collection and measurements

Data were recorded from central 2 plants per plot resulting in a total of 42 sampled plants. Observations were taken at 15 days after treatment (DAT), 30 DAT and at harvest. Growth parameters included peduncle height, number of leaves, number of branches and canopy cover. Yield attributes such as number of inflorescences, pods per inflorescence, seeds per pod, Thousand Grain Weight (TGW) and seed yield per plant were recorded following standard measurement procedures.

2.5 Statistical analysis

Data entry was done with the help of MS Excel following standard format then data were subjected to analysis of variance (ANOVA) appropriate to one-way randomized complete block design technique using RStudio. All the analyzed data were subjected to Duncan's Multiple Range Test (DMRT) for mean comparison at 5% level of significance and findings were discussed related with available literature (Gomez and Gomez, 1984).

3 Results and Analysis

3.1 Growth parameters

3.1.1 Peduncle height

The result showed that peduncle height was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 2). At 15 DAT, the maximum peduncle height was recorded from GA₃ at 50 ppm (106.33 cm) followed by GA₃ at 100 ppm (96.33 cm) which was statistically similar with NAA at 100 ppm (87 cm). Monoruzzaman et al. (2019) also reported the maximum peduncle height from GA₃ at 50 ppm. The control treatment gave the lowest peduncle height (58.67 cm) which was statistically at par with NAA at 50 ppm (61.67 cm). At 30 DAT, the maximum peduncle height was recorded from GA₃ at 100 ppm (136.33 ppm) which was statistically similar with GA₃ at 50 ppm (118.83 cm) whereas the minimum peduncle height was recorded from control treatment (95.33 cm).

At harvest, the mean peduncle height was found to be 121.61 cm. The maximum peduncle height was recorded from GA₃ at 100 ppm (136.33 cm) which was statistically similar with NAA at 100 ppm (130.33 cm). The minimum peduncle height was recorded from control treatment (110.33 cm) which was statistically at par with NAA at 50 ppm (113 cm) and NAA at 75 ppm (117.33 cm). However, the minimum peduncle height was recorded all in control treatment at 15 DAT, 30 DAT and a harvest.

3.1.2 Number of leaves

The analyzed data revealed that the number of leaves was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 2).

At 15 DAT, the mean leaf number was found to be 131.52. The maximum leaf number was observed from GA₃ at 50 ppm (147.33) followed by GA₃ at 100 ppm (136) and NAA at 100 ppm (41.33). Kumar et al. (2023) also reported the maximum and minimum leaf number from GA₃ at 50 ppm and from control treatment. The minimum leaf number was observed from control treatment (120.33) and NAA at 50 ppm (120.33).

At 30 DAT, the mean leaf number was found to be 137.85. The maximum leaf number was recorded from GA₃ at 50 ppm (167.67) and NAA at 100 ppm (162) whereas the minimum leaf number was observed from control treatment (105).

However, the maximum and minimum leaf number was recorded from GA₃ at 50 ppm and control treatment at both 15 DAT and 30 DAT.

3.1.3 Number of branches

It is clear from the data that the application of GA₃ and NAA significantly affected on number of branches of cabbage at 30 DAT whereas the treatment was found non-significant at 15 DAT (Table 2). It might be due to various environmental factors like light, temperature and nutrient availability which can modulate the plant's response to hormones. The mean branch number at 15 DAT was found to be 31.14. The maximum branch number was observed from GA₃ at 100 ppm (49.83) which was significantly similar with NAA at 100 ppm (43.17). The minimum number of branches was observed from control treatment (27.33) along with GA₃ at 50 ppm (29.17) and GA₃ at 75 ppm (29.17) which was statistically at par with NAA at 50 ppm (32.83) and NAA at 75 ppm.

3.1.4 Canopy cover

The analyzed data revealed that the canopy cover was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 2). The canopy cover was also found non-significant at 15 DAT. The mean canopy cover recorded was 31.14 cm.

Table 2 Effect of different concentrations of GA₃ and NAA on growth parameters of cabbage at THDC, Marpha, Mustang, 2024

Treatments	Peduncle height (cm)			Number of leaves		Number of branches		Canopy cover (cm)	
	15 DAT	30 DAT	At harvest	15 DAT	30 DAT	15 DAT	30 DAT	15 DAT	30 DAT
T ₁	58.67 ^c	95.33 ^d	110.33 ^c	120.33 ^d	105.00 ^e	28.33	27.33 ^c	64.25	95.33 ^d
T ₂	106.33 ^a	118.83 ^{ab}	120.00 ^{cd}	147.33 ^a	167.67 ^a	30.83	29.17 ^c	70.75	118.83 ^{ab}
T ₃	81.33 ^c	107.33 ^c	124.00 ^{bc}	128.00 ^e	129.00 ^{cd}	28.83	28.00 ^c	54.33	107.33 ^c
T ₄	96.33 ^b	124.67 ^a	136.33 ^a	136.00 ^b	136.67 ^{bc}	34.33	49.83 ^a	59.83	124.67 ^a
T ₅	61.67 ^c	117.17 ^b	113.00 ^{de}	120.33 ^d	123.67 ^d	30.33	32.83 ^{bc}	64.83	117.17 ^b
T ₆	72.33 ^d	112.33 ^{bc}	117.33 ^{cde}	132.33 ^{bc}	141.00 ^b	35.00	35.33 ^{bc}	60.37	112.33 ^c
T ₇	87.00 ^b	107.00 ^c	130.33 ^{ab}	136.33 ^b	162.00 ^a	30.33	43.17 ^{ab}	59.91	107.00 ^c
LSD (0.05)	8.39	6.35	7.26	4.96	9.39	11.45	12.07	14.28	6.35
SEm(±)	2.72	2.06	2.35	1.61	3.04	3.71	3.91	4.63	2.06
F-probability	***	***	***	***	***	ns	*	ns	***
CV (%)	5.86	3.19	3.35	2.12	3.83	20.67	19.33	12.94	3.19
Grand Mean	80.52	111.80	121.61	131.52	137.85	31.14	35.09	62.04	111.80

Note: Means with the same letter within a column do not differ significantly at p=0.05 by DMRT. *= Significant at 5% ($p \leq 0.05$), **= Significant at 1% ($p \leq 0.01$), ***= Significant at 0.1% ($p \leq 0.001$), ns= non-significant, SEm= Standard error of the mean, LSD= Least Significant Difference, CV= Coefficient of variance, DAT= Days after treatment

At 30 DAT, canopy cover was significantly affected by the application of different concentrations of GA₃ and NAA. The mean canopy cover was 111.80 cm. The maximum canopy cover was recorded from GA₃ at 100 ppm (124.67 cm) which was statistically at par with GA₃ at 50 ppm (118.83 cm). GA₃ at higher concentration leads to leaf expansion which helps to spread plants. This similar work was presented by Dev et al. (2020) who reported that maximum canopy cover would be obtained with the treatment of highest dose of GA₃. GA₃ at 75 ppm (107.33 cm), NAA at 75 ppm (112.33 cm) and NAA at 100 ppm (107 cm) showed the similar effect on canopy cover whereas the minimum canopy cover was observed from control treatment (95.33 cm).

3.2 Yield parameters

3.2.1 Number of inflorescences

The analyzed data revealed that the number of inflorescences was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 3). The mean number of inflorescences was found to be 127.04. The higher number of inflorescences was found from GA₃ at 100 ppm (140) which was statistically similar to GA₃ at 75 ppm (134.67) and NAA at 100 ppm (136). Similarly, GA₃ at 75 ppm and NAA at 100 ppm showed the similar effects which was statistically similar with GA₃ at 50 ppm (131). The lower number of inflorescences was observed in control treatment (104.67) as usual like in other parameters.

3.2.2 Number of pods per inflorescence

The analyzed data revealed that the number of pods per inflorescence was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 3). The mean number of pods per inflorescence was found to be 15.99. When the data for the number of pods per inflorescence parameter were analyzed, the best results were given by the application of GA₃ at 50 ppm (22.19) followed by GA₃ at 100 ppm (17.10) and NAA at 100 ppm (16.67). Even though the GA₃ at 100 ppm and NAA at 100 ppm treatment statistically mirrored each other, the effect of GA₃ at 100 ppm gave the maximum number of pods per inflorescence. GA₃ at 75 ppm (14.37) showed the intermediate effect which was statistically similar with NAA at 50 ppm (15.55) and NAA at 75 ppm (14.05). Number of pods per inflorescence was found lower in control treatment (12).

3.2.3 Number of seeds per pod

The analyzed data revealed that the number of seeds per pod was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 3). The mean number of seeds per pod was found to be 23. When the data for the number of seeds per pod parameter were analyzed, the best results were given by the application of GA₃ at 50 ppm (24.67) which was statistically at par with GA₃ at 75 ppm (23.33) and GA₃ at 100 ppm (24). All NAA treatments with concentrations 50 ppm (22.67), 75 ppm (22.33) and 100 ppm (22.33) gave the similar results. Although they gave the similar results, NAA at 50 ppm gave the higher seeds per pod. GA₃ at 75 ppm gave the intermediate effects of all i.e. 23.33. The number of seeds per pod was found lower in control treatment (21.67) as usual.

3.2.4 Thousand grain weight (TGW)

The analyzed data revealed that the Thousand Grain Weight (TGW) was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 3). When the data for the Thousand Grain Weight (TGW) parameter were analyzed, the best results were given by the application of GA₃ at 50 ppm (1.17 g) and GA₃ at 100 ppm (1.28 g). Even though the GA₃ at 50 ppm and GA₃ at 100 ppm treatment statistically mirrored each other, the effect of GA₃ at 100 ppm was greater than the effect of GA₃ at 50 ppm. The lowest Thousand Grain Weight (TGW) was recorded from the control treatment (1.17 g) and from NAA at 50 ppm (1.17 g).

3.2.5 Seed yield

The analyzed data revealed that the seed yield was significantly influenced by the application of different concentrations of GA₃ and NAA (Table 3). When the data for the seed yield were analyzed, the best results were given by the application of GA₃ at 50 ppm (2.91 t/ha) followed by NAA at 100 ppm (2.53 t/ha) which was statistically similar with GA₃ at 100 ppm (2.68 t/ha). NAA at 75 ppm (1.82 t/ha) was statistically at par with NAA at 50 ppm. The control treatment gave the lowest seed yield (1.48 t/ha) like other parameters which was expected.

Table 3 Effect of different concentrations of GA₃ and NAA on yield parameters of cabbage at THDC, Marpha, Mustang, 2024

Treatments	Number of inflorescences	Number of pods per inflorescence	Number of seeds per pod	TGW (g)	Yield (t/ha)
T ₁	104.67 ^e	12.00 ^d	21.67 ^c	1.17 ^e	1.48 ^e
T ₂	131 ^b	22.19 ^a	24.67 ^a	1.27 ^a	2.91 ^a
T ₃	134.67 ^{ab}	14.37 ^c	23.33 ^{abc}	1.21 ^c	2.21 ^c
T ₄	140 ^a	17.10 ^b	24.00 ^{ab}	1.28 ^a	2.68 ^{ab}
T ₅	118 ^d	15.55 ^{bc}	22.67 ^{bc}	1.17 ^e	1.65 ^{de}
T ₆	125 ^c	14.05 ^{cd}	22.33 ^{bc}	1.19 ^d	1.82 ^d
T ₇	136 ^{ab}	16.67 ^b	22.33 ^{bc}	1.24 ^b	2.53 ^b
LSD (0.05)	5.73	2.11	1.60	0.01	0.22
SEm(±)	1.86	0.68	0.51	0.005	0.07
F-probability	***	***	*	***	***
CV (%)	2.53	7.43	3.91	0.81	5.83
Grand Mean	127.04	15.99	23	1.21	2.18

Note: Means with the same letter within a column do not differ significantly at $p=0.05$ by DMRT. *= Significant at 5% ($p\leq 0.05$), **= Significant at 1% ($p\leq 0.01$), ***= Significant at 0.1% ($p\leq 0.001$), ns= non-significant, SEm= Standard error of the mean, LSD= Least Significant Difference, CV= Coefficient of variance, DAT= Days after treatment

4 Discussion

The growth and yield parameters of cabbage were significantly affected by the application of different concentrations of GA₃ and NAA. Notably, GA₃ at 50 ppm produced the highest seed yield (2.91 t/ha) and also resulted in superior performance across several traits, including peduncle height, number of leaves, pods per inflorescence and seeds per pod. Similar findings were reported by Roy and Nasiruddin (2011) who observed maximum cabbage yield at 50 ppm, suggesting that moderate concentrations of gibberellin are more effective than higher doses for optimizing plant productivity. Likewise, Kumar et al. (2023) reported the highest leaf number in plants treated with GA₃ at 50 ppm and the lowest in the control treatment which is in agreement with the findings of the present study. The enhanced leaf production observed under GA₃ application may be attributed to its stimulatory effect on the apical meristem, promoting cell division, cell elongation and nucleo-protein synthesis thereby increasing leaf initiation and development.

Furthermore, GA₃ at 50 ppm significantly increased the number of inflorescences, pods per inflorescence and seeds per pod, aligning with the findings of Dev et al. (2020). This suggests that a lower concentration of GA₃ enhances growth and seed yield more effectively than higher doses, which is consistent with the observation by Moniruzzaman et al. (2019) and Prodhan et al. (2022) that excessive GA₃ can induce disproportionate vegetative growth or physiological stress, ultimately reducing reproductive output.

NAA treatments also improved growth and yield parameters compared with the control, particularly at 100 ppm, which produced seed yield statistically comparable to GA₃ at 100 ppm. Auxins such as NAA are known to enhance cell enlargement, nutrient translocation and sink strength thereby supporting reproductive growth and seed formation. However, the overall response of cabbage to NAA was lower than that observed for GA₃ indicating that gibberellin played a more dominant role in regulating flowering and seed yield under the environmental conditions of Mustang. Similar positive effects of NAA on cabbage growth and yield have been reported by Neelam et al. (2023).

From a practical perspective, the findings indicate that foliar application of GA₃ at 50 ppm during head initiation and flowering can be recommended as an effective strategy for improving cabbage seed production in temperate regions of Nepal. Nevertheless, the study was conducted at a single location during one growing season. Therefore, further multi-location and multi-year studies are necessary to validate these findings under varying environmental conditions. Further investigations should also examine physiological and biochemical responses

associated with plant growth regulator application to better understand the mechanisms responsible for enhanced seed yield.

5 Conclusion

On the basis of the above findings, it can be concluded that different concentrations of GA₃ and NAA has significant effect on growth parameters like peduncle height, number of leaves, number of branches, canopy cover and yield parameters like number of inflorescences, number of pods per inflorescence, number of seeds per pod, Thousand Grain Weight (TGW) and seed yield per plant.

GA₃ at different ppm has shown more effect than NAA at different concentrations whereas the control treatment has the least effect in all measured parameters above. GA₃ at 50 ppm has given the best result in maximum parameters like plant height, leaf number, number of pods per inflorescence, TGW and seed yield per plant.

Authors' contributions

ST handled the data collection, data analysis and manuscript writing. SK, AC and NP helped in sample collection. PNA and AS served as the primary supervisor and helped in choosing the research topic. BBK involved in the manuscript revision and providing the final structure to the manuscript. All authors read and approved the final manuscript.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be constructed as a potential conflict of interest.

References

- Ahmed N., Waheed A., Hamid F.S., Ahmed I., Khan M.A., Aslam S., Younis M.A., Ali S., Khan N., and Bashir M., 2019, Response of cabbage cultivars to different concentrations of gibberellic acid, *Pakistan Journal of Agricultural Research*, 32(4): 562-565.
<https://doi.org/10.17582/journal.pjar/2019/32.4.562.565>
- Aryal B., Neupane S., Pandey B., Shah S., and Tiwari A., 2022, Socio-economic analysis of vegetable seed production in Nepal, *Agricultural Science & Technology*, 14(2).
- Chaurasiya J., Meena M., Singh H., Adarsh A., and Mishra P., 2014, Effect of GA₃ and NAA on growth and yield of cabbage, *An International Quarterly Journal of Life Science*: 1139-1141.
- Dev R., Singh V.K., Raj S., and Shukla K.C., 2020, Effect of plant growth regulators on growth and yield of cabbage (*Brassica oleracea* var. *capitata*), *Journal of Pharmacognosy and Phytochemistry*, 9(3): 1024-1026.
<https://doi.org/www.phytojournal.com>
- Devi S., Choudhary M., Jat P.K., Singh S.P., and Rolaniya M.K., 2017, Influenced of organic and biofertilizers on yield and quality of cabbage (*Brassica oleracea* var. *capitata*), *International Journal of Chemical Studies*, 5(4): 818-820.
- Gomez K.A., and Gomez A.A., 1984, Statistical procedures for agricultural research, The International Rice Research Institute.
- Kumar A., Bisen R.K., Verma S.K., Agrawal H.P., Chaure N.K., Tirkey P.L., Mishra S., Kumar Y., Patel M., and Patel C.R., 2023, Effect of foliar application of plant growth regulators on growth and yield of cabbage (*Brassica oleracea* var. *capitata* L.), *The Pharma Innovation*, 12(11): 412-415.
<https://doi.org/www.thepharmajournal.com>
- MOAD, 2016, Statistical information on Nepalese agriculture 2072-2073.
- MOAD, 2018, Harihar Bhawan, Lalitpur: Agriculture Information and Communication Center.
- Moniruzzaman M., Khatoon R., and Rahman M.M., 2019, Effect of GA₃ and NAA on growth and yield of cabbage, *Bangladesh Journal of Agricultural Research*, 44(2): 367-376.
<https://doi.org/10.3329/bjar.v44i2.41824>
- Neelam J.K., Silas V.J., Singh A., and Goyal A.K., 2023, Effect of foliar spray of GA₃ and NAA on growth, yield and quality of cabbage, *The Pharma Innovation*: 291-294.
- Pokhrel D.S., and Rijal I.P., 2017, Statistical information on Nepalese agriculture, Nepal.
- Prodhan M.M., Sarker U., Hoque M.A., Biswas M.S., Ercisli S., Assouguem A., Ullah R., Almutairi M.H., Mohamed H.R.H., and Najda A., 2022, Foliar application of GA₃ stimulates seed production in cauliflower, *Agronomy*, 12(6): 1394.
<https://doi.org/10.3390/agronomy12061394>

- Roy R., and Nasiruddin K.M., 2011, Effect of different level of GA₃ on growth and yield of cabbage, Journal of Environmental Science and Natural Resources, 4(2): 79-82.
<https://doi.org/10.3329/jesnr.v4i2.10138>
- Sawant V.P., Naik D.M., Barkule S.R., Bhosale A.M., and Shinde S.B., 2010, Effect of foliar application of growth regulators on growth, yield and quality of cabbage cv. Golden Acre, The Asian Journal of Horticulture, 5(2): 495-497.
- Shrestha S.L., 2019, Performance evaluation of cabbage (*Brassica oleracea* Capitata) cultivars in mid-hills of Nepal for winter season production, International Journal of Horticulture, Agriculture and Food Science, 3(2): 91-96.
<https://doi.org/10.22161/ijhaf.3.2.7>
- Singh B.K., 2015, Influence of growth regulators on growth, yield and economics of cabbage varieties, Annals of Plant and Soil Research, 17(1): 41-44.
- Singh N.P., Bhardwaj A.K., Kumar A., and Singh K.M., 2018, Modern technology on vegetable production, New Delhi: CBS Publishers & Distributors Pvt. Ltd.
- Singh S.K., and Verma A., 2021, Effect of plant growth regulators (GA₃ and NAA) on yield of cabbage in hilly regions of Chattisgarh, The Pharma Innovation: 1903-1905.

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Feature Review

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Nutritional and Irrigation Strategies for High-Yield Peach Production

Hongpeng Wang¹, Xingzhu Feng² ✉¹ Biotechnology Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, China² Hainan Institute of Biotechnology, Haikou, 570206, Hainan, China✉ Corresponding author: xingzhu.feng@hitar.orgInternational Journal of Horticulture, 2026, Vol.16, No.3 doi: [10.5376/ijh.2026.16.0016](https://doi.org/10.5376/ijh.2026.16.0016)

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Abstract The peach industry is currently facing pressure to stabilize yield, improve quality, save water and fertilizer, reduce costs, and increase efficiency. Water and mineral nutrient management has therefore become a key factor affecting high-yield and high-quality peach cultivation. This study analyzes peach water requirements, nitrogen, phosphorus, and potassium supply, deficit irrigation, and coordinated water-fertilizer regulation. The results show that appropriate nitrogen supply, balanced phosphorus and potassium ratios, and supplementation with micronutrients such as calcium, boron, and zinc can promote flowering, fruit set, fruit enlargement, and quality formation. Measures such as drip irrigation, integrated water and fertilizer management, regulated deficit irrigation, and partial root-zone drying can improve water use efficiency, enhance soluble solids, firmness, sugar-acid ratio, and mineral nutrient content, while reducing fertilizer loss and environmental risks. The study indicates that high-yield peach cultivation should be precisely regulated according to tree demand, soil nutrient supply, and phenological stages. Establishing an integrated water and fertilizer management system that combines water saving, fertilizer saving, high yield, superior quality, and ecological safety is of great significance for promoting the green and sustainable development of the peach industry.

Keywords Peach tree; High-yield cultivation; Integrated water and fertilizer management; Drip irrigation; Fruit quality

1 Introduction

Peach is one of the most important temperate fruit trees in the world and occupies a prominent position in global temperate fruit production, ranking second only to apple in terms of cultivation area and yield (Kumar and Kaur, 2021; Manganaris et al., 2022). In countries such as Spain, Tunisia, Egypt, the United States, and Ethiopia, large-scale commercial peach production has been established, providing important support for farmers' income and rural economies (Iglesias and Echeverría, 2022; Toumi et al., 2022). Peach trees enter the fruiting stage relatively early and have high yield potential per unit area. Under proper management, they can generate favorable economic returns, which has made them highly valued by growers for a long time (Kumar and Kaur, 2021). However, in recent years, affected by rising labor costs, declining grower profits, and intensified market competition in some major production areas, the peach industry has faced the dual pressure of stabilizing yield and improving quality while reducing costs and increasing efficiency (Manganaris et al., 2022). Consumers' requirements for fruit size, firmness, flavor, color, and nutritional quality are also increasing. Unstable fruit quality can directly affect peach consumption and the profitability of the industry (Anthony and Minas, 2021; Manganaris et al., 2022).

In high-yield peach cultivation, water and mineral nutrition are key factors affecting tree growth, fruit set, fruit enlargement, and quality formation. Insufficient nitrogen supply can weaken root growth, flower bud quality, and nutrient absorption capacity, thereby affecting yield. In contrast, excessive nitrogen application may lead to excessive vegetative growth, reduced fruit quality, increased disease risk, and nutrient loss (Nava et al., 2022). Phosphorus and potassium are associated with flowering and fruit set, sugar transport, fruit weight formation, and stress resistance. Therefore, an appropriate nitrogen, phosphorus, and potassium ratio is an important basis for achieving high yield and superior quality in peach production (Zayan et al., 2016; Dbara et al., 2018). Field studies have shown that appropriate fertilization at key stages such as budbreak, flowering, and fruit development

can increase yield per tree and improve fruit size, soluble solids content, color, and phenolic composition. However, excessive phosphorus application may be unfavorable for sugar accumulation (Maatallah et al., 2024). Excessive fertilization also increases production costs and the risk of environmental pollution. Therefore, optimizing fertilization rate, application timing, and internal nutrient balance of trees has become an important direction in peach orchard management (Casamali et al., 2021a; Nava et al., 2022; Mosie et al., 2025).

Irrigation management also determines peach yield and quality, especially in semi-arid and arid regions and areas with limited water resources (Pascual et al., 2016; Toumi et al., 2022). Supplemental irrigation can promote canopy growth, trunk thickening, photosynthesis, and early yield formation, with more pronounced effects in dry years (Fisk et al., 2015; Casamali et al., 2021a). However, severe water stress during the later stage of fruit development can reduce fruit size, quality, and economic returns (Fisk et al., 2015). Zhou et al. (2017) showed that moderate deficit irrigation can maintain yield while improving individual fruit weight, soluble solids content, vitamin C content, firmness, sugar-acid ratio, and water use efficiency. In arid regions of Tunisia, sustained deficit irrigation and partial root-zone drying treatments also improved fruit dry matter, sugars, phenolics, and mineral element contents (Toumi et al., 2022). A meta-analysis further indicated that regulated deficit irrigation generally helps improve water use efficiency in peach trees, while yield losses are usually within a controllable range (Ali et al., 2024).

With the development of high-density cultivation, dwarf tree forms, mechanized management, and increasing water constraints under climate change, traditional fertilization and irrigation practices can no longer fully meet the needs of modern peach orchards for high yield and high quality (Anthony and Minas, 2021; Iglesias and Echeverría, 2022). Integrated water and fertilizer management combines water supply and fertilizer application through drip irrigation, micro-sprinkler irrigation, and other approaches. It enables synchronized, small-dose, repeated, and precise water and nutrient supply during key growth stages, helping improve water and nutrient use efficiency while reducing input waste and environmental risks.

This study focuses on water management, nitrogen, phosphorus, and potassium nutrient supply, and the coordinated regulation of deficit irrigation and fertilization in peach trees. It aims to provide technical references for stable yield, high productivity, superior quality, and sustainable management of peach orchards.

2 Physiological Basis of Peach Yield Formation

2.1 Flowering, fruit set, and fruit development

High yields and good fruit size are associated with balanced NPK supply, with peak N demand around flowering and fruit set (Figure 1). In commercial orchards, NPK supply regimes that emphasized relatively high N during S2 (flowering/fruit set) produced the highest yields (50-68 kg/tree) and supported later fruit size and quality (Maatallah et al., 2024). N is a key macronutrient for leaf development, photosynthetic capacity, and sugar formation, and peak N demand in stone fruits occurs at bud break, flowering, and fruit set (Chawla and Sharma, 2025). Inadequate N reduces flower bud quality and effective fruiting, and also impairs root growth and water and nutrient uptake (Nava et al., 2022).

Peach fruit development proceeds through four stages (S1-S4), with rapid cell division and growth in S1, pit hardening in S2, a second exponential growth phase in S3, and final ripening in S4 (Zhang et al., 2022). N supply during pit hardening and fruit expansion directly affects yield, fruit quality, and metabolite composition, particularly carbon and amino acid metabolism (Zhang et al., 2022). Excessive P supply, in contrast, can be negatively correlated with total sugar content in the fruit (Maatallah et al., 2024).

During the rapid fruit expansion stage (S3/fruit expansion), water demand is high because fruit size increases quickly and large amounts of carbohydrates are required (Zhang et al., 2022). Studies in semi-arid conditions show that water deficit from mid-pit hardening to harvest significantly reduces shoot and fruit growth, with growth more sensitive to water shortage than photosynthesis (Rahmati et al., 2015). As tree water status declines

beyond a threshold (midday stem water potential around -1.5 MPa), daily net carbon gain becomes negative, indicating that carbon assimilation no longer meets the respiratory and growth demands of shoots and fruits.

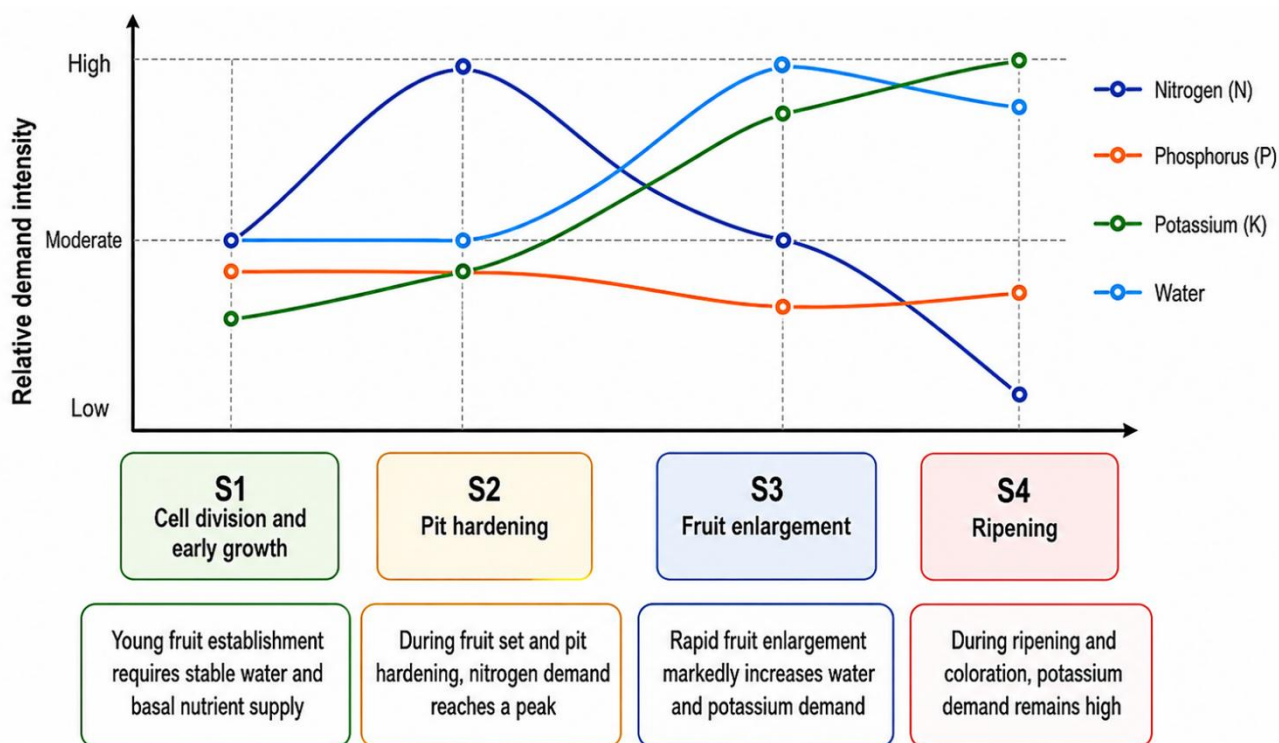


Figure 1 Changes in water and nutrient demand across peach fruit developmental stages (S1-S4)

Image caption: Peach trees show stage-dependent water and nutrient requirements, with nitrogen peaking at flowering and fruit set, while water and potassium demand increase markedly during fruit enlargement and ripening stages

2.2 Source–sink relationship in peach trees

Leaf photosynthesis provides the primary carbohydrate source for developing fruits. N is central to leaf development and photosynthetic capacity in stone fruits, supporting sugar and carbohydrate formation for fruit growth (Chawla and Sharma, 2025). Water deficit reduces leaf photosynthesis by decreasing stomatal conductance and by reducing total leaf area, thereby lowering whole-tree carbon assimilation (Rahmati et al., 2015). Altering the source-sink ratio through thinning (reducing fruit number per leaf area) can transiently decrease photosynthesis and cause sugar accumulation in leaves, indicating feedback limitation when sink demand is low (Andrade et al., 2019). Application of 5-aminolevulinic acid (ALA) can enhance leaf photosynthetic gas exchange capacity for at least one month and enlarge “source” volume, increasing carbon fixation in leaves (Liang et al., 2023). Fruit sink strength—its capacity to import and utilize assimilates—depends on both sink size and activity. A realistic estimate of sink strength is the sum of carbon gained as dry weight plus carbon lost through respiration, with net sink strength determined by the product of sink size and sink activity (Bianco and Rieger, 2002).

In peach, both sorbitol and sucrose are major forms of translocated carbon, and their contents in fruit correlate positively with growth rate; enzyme activities involved in their metabolism are closely associated with sink strength across developmental stages (Bianco and Rieger, 2002). Under conditions of high crop load or limited assimilate availability, acid invertase activity and hexose:sucrose ratios increase, which can enhance fruit sink strength by raising hexose concentrations (Morandi et al., 2008). ALA treatments further strengthen fruit sink competition by increasing the proportion of radiolabeled carbon transported from leaves to fruits and reducing allocation to young leaves (Liang et al., 2023).

At the whole-tree level, simple carbon balance models in water-stressed peach show that sinks (fruits and shoots) demand carbon for growth and maintenance respiration, and once daily carbon assimilation falls below this demand, net carbon gain becomes negative and carbohydrate reserves in the trunk decline (Rahmati et al., 2015). This illustrates that fruit set and final yield are constrained not only by local fruit sink strength but also by whole-tree carbon balance under the prevailing irrigation regime.

2.3 Root growth and resource uptake

Root distribution and nutrient absorption capacity strongly influence how trees exploit soil water and nutrients. Peach rootstocks differ in their efficiency for N, P, and K uptake, transport, and use; rootstocks with greater efficiency in nutrient transport and use show superior growth parameters, indicating better adaptation to low nutrient availability (Menegatti et al., 2021). In ‘Okinawa Roxo’ rootstock, complete nutrient solutions that optimize N, P, and K contents promote strong root growth, better dry-weight partitioning, and morphophysiological characteristics suitable for grafting within three months (Souza et al., 2019).

Root system architecture (depth and angle) varies among peach × (peach × almond) backcross populations; deeper, more vigorous root systems with narrower angles are better able to explore and exploit water and nutrients in deep sandy soils (Lesmes-Vesga et al., 2023). Soil moisture and root-zone conditions directly affect root activity and water/nutrient uptake. Increasing soil water content and N supply raises leaf area and leaf, shoot, and root hydraulic conductivities in peach seedlings, improving water transport and growth under low soil moisture (Zhang et al., 2014). Conversely, severe water deficit in orchards reduces root length density by about 73% compared with well-irrigated trees, while partial rootzone drying reduces root length by about 42%, indicating that continuous deficit irrigation imposes stronger constraints on root system development than alternated wet–dry zones (Abrisqueta et al., 2008).

Roots are concentrated mainly in the upper 0.55 m of soil, especially at 0.40-0.55 m depth, with more than 88% of roots being very thin (<0.5 mm), highlighting the importance of maintaining moisture and nutrients in this zone (Abrisqueta et al., 2008). Root-zone aeration can further enhance root activity and nutrient availability. In a peach orchard, aeration increased soil oxygen, raised the abundances of N-fixing and K-solubilizing microorganisms, and increased soil alkaline N, available K, organic matter, and numbers and thickness of new white roots (Sun et al., 2022b). These changes also altered plant N and K status and increased the shoot K:N ratio, which was associated with improved fruit quality (Sun et al., 2022a). Soil management practices, including cover crops and bare soil strips, influence root growth, tree water use, and NO₃-N availability in adjacent soil; tree growth is allometrically related to root growth under these heterogeneous soil conditions.

3 Nutritional Strategies for High-Yield Peach Production

3.1 Macronutrient management

Nitrogen is the primary driver of shoot growth, leaf area development, and fruit sink strength. In peach, an annual N supply is required due to its mobility and leaching risk, with early-season soil applications commonly recommended to stimulate spring shoot growth and blossom development and to support ovary growth and fruit set (Tsoumanis et al., 2025). Nitrogen fertilization directly affects yield and fruit quality, but both deficiency and excess are detrimental: low N reduces flower bud quality, root growth, and fruiting capacity, whereas excessive N promotes vegetative overgrowth, lowers fruit quality, and increases disease incidence (Nava et al., 2022).

Field studies show that moderate N rates (around 200 kg N/ha) can maximize yield without sacrificing quality, and that the timing of N application (e.g., pit hardening vs. fruit expansion) significantly influences yield, leaf N status, and quality traits (Zhang et al., 2022). Integrated omics analyses further indicate that pre-harvest N modifies carbon and amino-acid metabolism and flavonoid biosynthesis, helping to explain stage-specific effects on fruit growth and quality.

Phosphorus and potassium act mainly on flowering, fruit growth, and sugar accumulation. P, N, and K together are essential macronutrients for Rosaceae fruit yield and quality, affecting fruit development and postharvest

performance (Bai et al., 2021). In commercial orchards, combinations of N-P-K adjusted by phenological stage have been shown to increase total yield and improve fruit size, weight, and soluble solids, particularly when N is emphasized around flowering and K during fruit development and ripening (Maatallah et al., 2024). However, high P supply can be negatively correlated with total sugar content, underscoring the need for balanced P inputs. (Maatallah et al., 2024). Foliar potassium (often combined with silicon) additionally enhances sugar translocation, coloration, soluble solids, firmness, and postharvest quality when applied at fruit set, stone hardening, and physiological maturity (Abidi et al., 2023).

3.2 Micronutrient supplementation

Calcium, boron, and zinc play crucial roles in fruit set, structural integrity, and quality formation. Soil and foliar Ca supply influences cell wall strength and postharvest behavior across Rosaceae fruits (Bai et al., 2021). In peaches and nectarines, foliar Ca applications increase fruit Ca content, especially when applied in late fruit development, with Ca retained mainly in the flesh and skin, which are critical for eating quality and shelf life (Carrasco-Cuello et al., 2024).

Boron is indispensable for cell wall formation, flowering, and fruit set; its imbalance reduces pollination success, fruit set, yield, and quality, and can increase acidity and physiological disorders (Thakur et al., 2023). Foliar B or Zn sprays in peach increase fruit set, yield, and quality traits such as TSS, TSS:acidity ratio, ascorbic acid, and firmness, while raising leaf B and Zn concentrations (Ali et al., 2019b; Muradi and Godara, 2020).

Deficiency symptoms of these micronutrients can manifest as poor flowering, low fruit set, small or deformed fruits, and increased physiological disorders. Boron deficiency is highlighted as one of the most widespread trace-element problems, producing a wide range of symptoms in young tissues and substantially reducing yield and quality (Thakur et al., 2023). In soil-based surveys of peach orchards, available B and Ca strongly influence single fruit weight and soluble solids, emphasizing the importance of maintaining adequate levels to avoid hidden deficiencies (Sun et al., 2022a). Foliar fertilization is generally considered 10-20 times more efficient than soil application for correcting micronutrient deficiencies in fruit trees, because it delivers nutrients directly to metabolically active leaves and developing fruit (Muradi and Godara, 2020).

3.3 Fertilization methods and timing

Basal soil fertilization and in-season topdressing form the backbone of macronutrient supply in many peach orchards. Early soil applications rich in N (often in 2-1-1 N:P:K ratios) before blossom are widely recommended to support spring growth and flower initiation, followed by additional N (e.g., ammonium sulfate) at early fruit set to sustain ovary growth and fruit retention (Tsoumanis et al., 2025). Multi-year trials combining intra-row spacing with N-P-S blends show that intermediate spacing and moderate basal rates (e.g., 150 kg/ha) can maximize yield, fruit weight, and economic return (Mosie et al., 2025).

Split N applications targeted to reproductive growth stages improve uptake and reduce environmental losses; isotope tracing in high-input orchards reveals that only about one-third of applied N is taken up by the tree, with substantial portions remaining in soil or lost to the environment, suggesting that total rates can be reduced by about 30% while focusing on reproductive stages (Yang et al., 2024). Foliar fertilization during key growth stages complements soil applications and allows rapid correction or strategic boosting of particular nutrients.

Foliar N-fixing biofertilizers applied at fruit appearance and full development can enhance chlorophyll content, shoot growth, and fruit weight while decreasing reliance on synthetic N sources (Tsoumanis et al., 2025). Foliar K (often as potassium-silicon) at fruit set, stone hardening, and maturity improves fruit weight, firmness, soluble solids, titratable acidity, and postharvest resistance, illustrating the value of stage-specific sprays (Abidi et al., 2023). Similarly, foliar B, Zn, and Fe sprays applied once or twice from early spring significantly increase yield, fruit size, TSS, ascorbic acid, and leaf micronutrient content while reducing acidity, with double sprays outperforming single applications (Ali et al., 2019a; Muradi and Godara, 2020).

4 Irrigation Strategies for Peach Yield Improvement

4.1 Water requirement at different growth stages

During flowering and young fruit development, avoiding severe water stress is essential for canopy growth, carbon acquisition and early yield formation. In humid subtropical conditions, daily evapotranspiration of young peach trees peaks during active shoot development, and accurate crop coefficients allow scheduling to avoid both stress and over-irrigation (Zambrano-Vaca et al., 2020).

Field studies show that non-irrigated trees under drought have markedly reduced canopy volume, trunk growth, leaf water potential and photosynthesis, with lower commercial yields than irrigated trees, highlighting the importance of supplying adequate water from establishment through early cropping (Casamali et al., 2021b). Water requirements and sensitivity change as fruits enlarge and mature. Soil-water-potential thresholds for triggering irrigation differ among stages: stem and fruit growth become progressively less sensitive to deficits from stage I to III, and irrigation at moderate soil water potentials (around -10 to -17 kPa) promotes both fruit growth and assimilate allocation to fruit (Lou et al., 2024).

Studies imposing water shortage at specific growth stages report that deficits from flowering to early growth (stage I) cause the largest yield reductions, whereas moderate deficits during stone hardening or mid-season can save 25%-50% of water with limited effects on yield and improved color and soluble solids (AboOgiela, 2021).

4.2 Irrigation methods in peach orchards

Modern orchards commonly use drip or micro-sprinkler irrigation. In young trees under variable rainfall, irrigation-regardless of method-improves water status, growth, and early yield compared with rainfed conditions, while drip uses substantially less water than micro-sprinklers. A related study on nitrogen partitioning likewise found higher cumulative N removal (reflecting greater growth) in irrigated than in non-irrigated trees, and ~38% water savings with drip versus micro-sprinkler irrigation (Casamali et al., 2021b).

Long-term comparisons including furrow (flood-type) irrigation indicate that drip and micro-sprinkler systems can match yields with less water and fewer quality penalties. Over 10 years, postharvest deficit irrigation under furrow, drip, or micro-sprinkler saved up to 40% water without significant reductions in yield or key quality attributes; surface drip in particular maintained soil water better than furrow and micro-spray under deficit conditions (Zhang et al., 2017; Wang et al., 2020). Broader meta-analysis across crops confirms that drip typically produces higher yields and water-use efficiency than flood, border, furrow, sprinkler, and even micro-sprinkler irrigation, especially under water shortage (Yang et al., 2023).

4.3 Deficit irrigation and water-saving approaches

Regulated deficit irrigation (RDI) and related strategies deliberately apply less than full crop evapotranspiration during periods when trees are less sensitive, aiming to balance yield and quality. In semi-arid Spain, sustained deficit ($\approx 62.5\%$ of full) and RDI (50% during stone hardening) often produced fruit yields similar to full irrigation, with only modest reductions in average fruit weight but higher soluble solids and sugar/acid ratios, suggesting improved commercial quality with water savings (Faci et al., 2014).

In Morocco, RDI at 75% ET_c during slowdown stages allowed water savings of up to 25% in peach without yield loss, while 50% ET_c reduced yield and size but enhanced sugar/acid ratio and polyphenols (Razouk et al., 2020). RDI scheduled by stem-water-potential thresholds (-1.5 to -1.8 MPa) cut water use by 43%-65% without affecting fruit size or yield and even slightly improved quality (Mirás-Avalos et al., 2016). A broader review and case study in Morocco reported that sustained deficit irrigation of peach reduced water use by 20% without affecting yield or quality and increased water productivity by 33% (Laita et al., 2024).

Partial root-zone drying (PRD), through alternating irrigation on both sides of the root system, can further improve water-saving efficiency and enhance fruit quality. In arid regions of Tunisia, deficit irrigation and partial root-zone drying at 50% ET_c increased fruit dry matter content, firmness, soluble solids, phenolic compounds, and mineral element concentrations, thereby enhancing market value while reducing water use by half (Toumi et

al., 2022). Deficit irrigation and partial root-zone drying can save 48%-52% of water. Although yield losses are approximately 25%, water productivity is improved, making these strategies highly attractive in areas facing severe water scarcity. A study in Tunisia using saline drip irrigation found that deficit irrigation at 50% ET_c and PRD50 produced similar results, with yield reductions of 20%-25%. However, long-term soil salinity remained stable, and significant water savings were achieved, supporting the application of these practices in arid and salinized environments (Toumi et al., 2024).

5 Interaction Between Nutrition and Irrigation

5.1 Water–nutrient coupling mechanisms

Soil moisture is fundamental because nutrients are dissolved in water and transported with soil solution flow to the root surface, where they can be absorbed by trees. In sandy, coarse-textured soils typical of many peach orchards, improving soil moisture in the root zone increases water availability and also enhances solubility and accessibility of nitrogen, phosphate, and potassium (Hamza et al., 2025). Under drip irrigation, higher soil moisture near emitters supports better root function and fertilizer uptake, while drier zones between emitters limit nutrient movement and uptake.

Different irrigation regimes alter nutrient availability and use efficiency. In arid sandy soils, irrigation with magnetized water increased root-zone moisture, improved soil chemical properties, and led to higher nitrogen, phosphorus and potassium use efficiencies compared with non-magnetized water, indicating more effective fertilizer uptake under improved water conditions (Hamza et al., 2025). Supplemental irrigation in young peach orchards increases vegetative growth and total nitrogen removal compared with non-irrigated trees, reflecting higher biomass and nutrient uptake under better water supply (Casamali et al., 2021b).

5.2 Fertigation technology in peach production

Fertigation—applying water-soluble fertilizers through drip systems—directly integrates fertilization and irrigation in the active root zone (Figure 2). Drip irrigation is highlighted as highly efficient in delivering water to roots and enabling precise fertigation that matches crop needs, reducing leaching losses and improving nutrient use efficiency and yield compared with conventional methods (Sharma et al., 2024). Meta-analysis across Chinese crops shows drip fertigation increases yield by about 12%, water productivity by 26%, and nitrogen use efficiency by 34% compared with traditional surface irrigation plus broadcast fertilization, while reducing evapotranspiration (Li et al., 2021).

Optimizing fertilizer concentration and irrigation frequency under drip fertigation is essential to balance high yield with minimal nutrient losses. A review of nitrogen losses under drip systems identifies soil moisture, fertigation, and irrigation regime as core factors controlling nitrate leaching and gaseous losses, and notes a shift from focusing only on application amounts to integrated management of rates, methods, and timing (Wei et al., 2024). In intensive fruit orchards, drip fertigation combined with plant hedgerows reduced total nitrogen and phosphorus runoff losses by about 45% and 37% compared with conventional fertilization, while maintaining high fruit yields, showing that concentrating nutrients in the wetted root zone and using vegetative barriers can both improve efficiency and reduce pollution (Song et al., 2023).

5.3 Effects on yield and fruit quality

Interactions between irrigation and nutrition influence fruit size, weight, and yield per tree. Soil applications of nitrogen, potassium, and calcium in a drip-irrigated sandy peach orchard increased yield and fruit weight versus unfertilized controls; the best macronutrient combination nearly tripled yield from about 37-40 kg to 97-104 kg per tree (Ali et al., 2019a). Mild deficit irrigation (75% ET_c) in semi-arid China maintained total yield equal to full irrigation (100% ET_c) but produced fewer, larger fruits, effectively shifting assimilates to remaining fruit under limited water (Zhou et al., 2017). Under stronger deficit irrigation in arid Tunisia, yields were not reported, but deficit strategies (DI and PRD) at 50% ET_c improved internal quality traits and increased mineral concentrations in fruits, suggesting more concentrated uptake and allocation of nutrients under reduced water (Toumi et al., 2022).

Water-nutrient interactions also shape soluble solids, firmness, and appearance quality. In deficit-irrigated orchards, fruits often show higher soluble solids and improved sugar:acid balance compared with fully irrigated trees, as seen in semi-arid China where 75% ETC produced fruit with more soluble solids, vitamin C, firmer texture, and better color than 100% ETC (Zhou et al., 2017). In arid Tunisia, sustained deficit irrigation and partial root-zone drying increased dry-matter content, firmness (by 13%-15.5%), soluble solids (up to 14.3 °Brix), glucose, phenolic compounds, and mineral nutrients, enhancing nutritional and commercial value (Toumi et al., 2022).

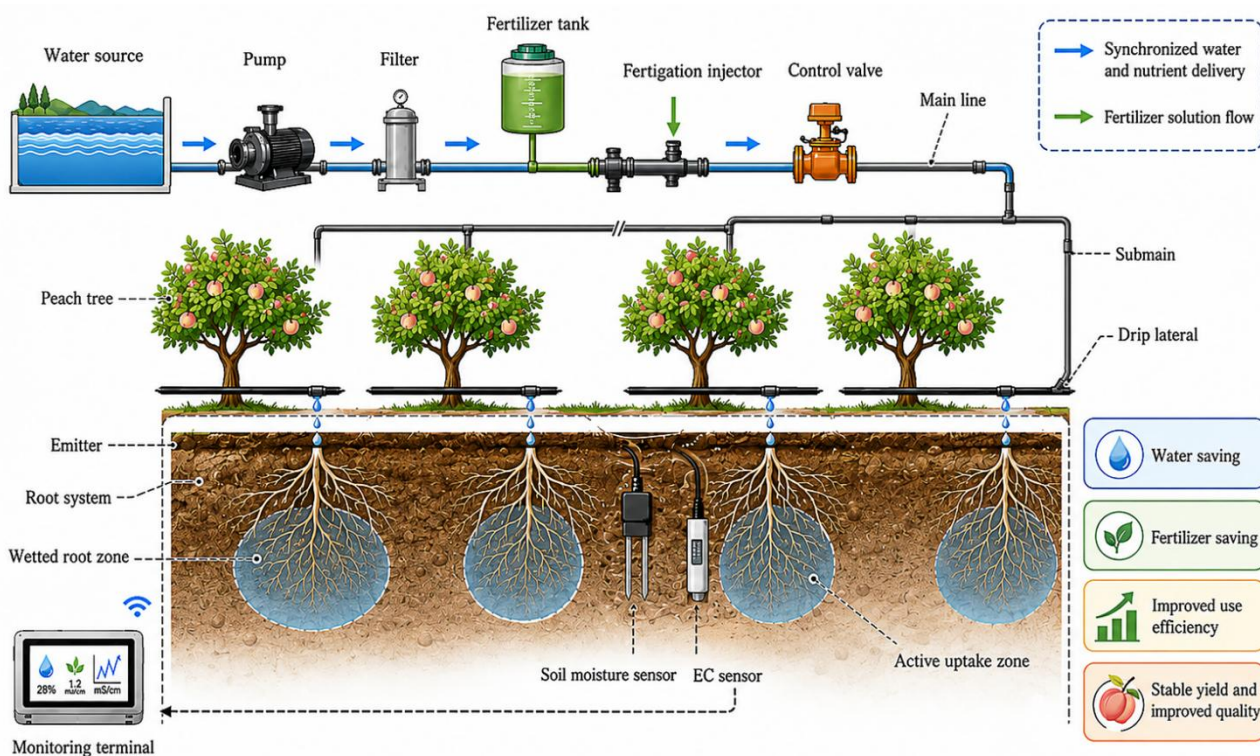


Figure 2 Drip fertigation system for integrated water and nutrient delivery

Potassium supply interacts with water regime: foliar K applied under full and deficit irrigation increased fruit size and soluble solids, with the highest soluble solids observed in potassium-sprayed trees under deficit conditions (100F+DI) (Dbara et al., 2018). In a fertilized, drip-irrigated sandy orchard, macronutrient applications increased fruit length, diameter, firmness, total soluble solids, and total sugars compared with unfertilized trees, confirming that adequate nutrition under efficient irrigation enhances both physical and internal quality attributes (Ali et al., 2019b).

6 Orchard Management Practices Supporting Nutrition and Irrigation

6.1 Soil management and organic amendments

Organic amendments can support fertilizer and water efficiency in peach orchards by improving soil structure, nutrient supply, and moisture buffering. In young orchards, annual applications of food-waste compost at 2× rate (≈20 t/ha pre-plant, then 10 t/ha annually) increased soil organic matter, phosphorus, and sodium in replant soils, improved soil moisture during the growing season, and produced larger trees and higher early yields than the unfertilized control, while allowing 80%-100% reduction of spring synthetic NPK inputs (Lawrence and Melgar, 2023). In bearing orchards, surface application of mixed compost (5-10 t/ha/yr) increased soil organic C and total N, reduced bulk density and water-filled pore space, and slightly improved fruit quality without significantly changing yield, indicating benefits for soil physical properties and carbon storage (Bruno et al., 2025).

Organic manures and mulches also influence tree nutrition and water relations. Fertigating slurry-composting-biofiltration liquid manure increased shoot growth, leaf N and K, soil exchangeable K, fruit weight, and yield compared with mineral fertilization, though leaf Ca and Mg declined and K accumulation risk required periodic soil testing (Park et al., 2013). Long-term compost or manure mulching in orchards more broadly reduces bulk density, loosens soil, increases nutrient elements and organic content, and improves crop yield and quality (Wang and Wang, 2016; Goldan et al., 2023). In mature peach orchards, municipal mulch with or without poultry litter buffered soil water relative to bare soil, reduced soil Cu, increased soil P and, in some cases, increased fruit size and tree growth, while enabling reductions in synthetic fertilizer inputs (Lawrence and Melgar, 2024).

6.2 Canopy management and crop load regulation

Canopy training and pruning determine light distribution, labor efficiency, and the balance between vegetative growth and fruiting. Traditional vase systems often show uneven light distribution and high pruning labor, whereas planar or multi-axis systems (central leader, Catalan vase, Quad-V, Tri-V) in intensive orchards improve light uniformity, fruit size, and soluble solids, while reducing total labor by up to 39% and production costs by about 15% (Iglesias and Echeverría, 2022; Oran et al., 2024). Within a given system, shorter pruning (heading bearing branches to 20-40 cm) reduced fruit number and yield per tree but increased average fruit weight and diameter, illustrating the trade-off between total yield and size (Saraginovski and Kiprijanovski, 2021).

Crop load regulation through fruit thinning is critical for balancing yield and quality and for efficient water use. In 'Xiahui 5', thinning twice at 20 and 40 days after full bloom increased individual fruit weight (to ~186 g), yield (~981 kg/ha), external and internal quality, and leaf water-use and CO₂-use efficiency, while saving labor compared with blossom thinning plus fruit thinning (Zhang et al., 2024). In 'Royal Gem', combinations of fruit thinning and summer pruning lowered total yield but significantly increased average fruit weight, firmness, and diameter, again showing that reducing sink number enhances fruit size and market value (Lesičar et al., 2017). Experiments with flat peaches confirm that higher crop loads increase total yield but reduce fruit weight and circumference and lower soluble solids content, whereas lower loads favor fruit quality and antioxidant compounds (Mazzoni et al., 2022).

6.3 Monitoring and diagnostic techniques

Leaf and soil diagnostics underpin rational fertilization that supports high yield without excess inputs. In peach orchards amended with compost, leaf sampling at standardized times after full bloom is used to quantify total N, P, K, Ca, Mg, and B, enabling evaluation of tree nutritional status under different compost rates and supporting adjustment of applications (Melo et al., 2016). Organic-amended orchards also highlight the need for periodic soil testing to detect nutrient accumulation (e.g., K under slurry manure fertigations) and guide safe long-term management (Park et al., 2013; Lawrence and Melgar, 2024). More broadly, intelligent orchard nutrient diagnosis is moving toward rapid, often spectral, detection of tree and soil nutrients combined with models to generate cultivar- and stage-specific nutrient standards for precision fertilization (Yuan et al., 2024).

For irrigation, soil-moisture sensing and automated scheduling tools link water status to tree demand. Traditional soil-based readings (TDR, capacitive sensors) and UAV imagery allow efficient monitoring of soil moisture, evapotranspiration, and canopy status in tree crops, supporting precise irrigation decisions (Tirado-Corbalá et al., 2021). Capacitance probes, already used in best-management programs, can measure volumetric water and ion content; they are especially sensitive to changes in K concentration and thus could feed decision-support systems for both irrigation and nutrient management (Strooboscher et al., 2024).

In drip-irrigated orchards, automated scheduling that combines FAO water-balance models with feedback from capacitance soil-moisture sensors has been shown (in apples) to match lysimeter-measured evapotranspiration in vigorous sectors while automatically reducing irrigation in less vigorous sectors, illustrating how sensor-driven systems can adapt water supply to spatial variability within orchards (Domínguez-Niño et al., 2020).

7 Challenges and Optimization of High-Yield Peach Production

7.1 Problems in current nutrient management

Many peach orchards still rely on uniform, empirically based fertilizer programs that ignore variability in soils and tree demand. In the southeastern United States, current N recommendations may be based on half-century-old work, with growing concern about over-fertilization, imbalanced vegetative/reproductive growth, fertilizer runoff, and inefficient use of financial resources (Casamali et al., 2021b). Excessive phosphorus use in perennial orchards can create very low P use efficiency ($\approx 15\%$) and large P surpluses, shifting soil P to more labile forms and sharply increasing the risk of P loss (Chen et al., 2022).

Low fertilizer-use efficiency is a major challenge in N management for peaches. Conventional high-N programs in China result in low N absorption, substantial N leaching and gaseous losses, and elevated greenhouse gas emissions (Xiao et al., 2019). In typical surface-broadcast systems, conventional management produced considerable NH_3 volatilization, N_2O emissions, and runoff, alongside only moderate yields (Yang et al., 2023). Spatial analyses in Brazilian orchards further show strong within-orchard variability of soil nutrients, yield, and fruit quality, meaning uniform fertilization leads to over-application in some zones and under-application in others (Oldoni et al., 2019).

7.2 Problems in current irrigation management

Integrated crop management has often been implemented only partially, with irrigation still applied empirically and usually in excess, wasting water and energy and raising greenhouse gas emissions (Maletsika et al., 2022). Energy-use analysis in Greek canning peaches identified irrigation as the single largest energy consumer and the practice with the highest impact on GHG emissions, mainly through electricity and fuel use (Maletsika et al., 2022).

Conversely, many new orchards elsewhere are not irrigated for several years after planting and depend solely on rainfall, leaving trees vulnerable to the increasingly frequent droughts (Casamali et al., 2021b). Under severe drought, non-irrigated young trees showed 56% smaller canopy volume, 39% smaller trunk cross-sectional area, 40% lower leaf photosynthesis, and reduced commercial yield compared with irrigated trees, with negative effects persisting in subsequent years. In arid Tunisia, cutting irrigation to 50% ET_c caused 20%-25% yield losses in mature orchards, underscoring the risk of unplanned, severe water cuts (Toumi et al., 2024).

7.3 Integrated optimization strategies

Precision fertigation links water and nutrient supply to tree demand in space and time. Drip irrigation, by delivering water directly to roots, provides an efficient platform for fertigation and precise matching of crop needs (Sharma et al., 2024). In perennial orchards, applying fertilizers through drip (fertigation) increased peach and apple yields and improved fruit quality compared with non-fertigated controls (Figure 3). Bag-controlled release fertilizers and super-large granular slow-release humic acid fertilizers further synchronize N release with peach growth stages, substantially increasing N use efficiency and reducing losses, while maintaining or increasing yield and net economic benefit (Xiao et al., 2019; Yang et al., 2023).

Region-specific, spatially explicit management models are another key optimization pathway. In Brazil, delineating two management zones in a 1.8-ha orchard based on soil and tree attributes creates opportunities for site-specific fertilization to correct over- and under-application (Oldoni et al., 2019). Precision irrigation protocols using thermal imagery and variable-rate drip at subfield scale in a commercial peach orchard maintained stem water potential within target ranges and improved water productivity in responsive management cells, showing the value of downscaling management within orchards (Katz et al., 2023). At a broader scale, deficit irrigation case studies in Moroccan peaches demonstrate that sustained deficit can reduce water use by 20% without affecting yield or quality and increase water productivity by 33%, though adoption is limited by conceptual ambiguity and risk perceptions (Laita et al., 2024).

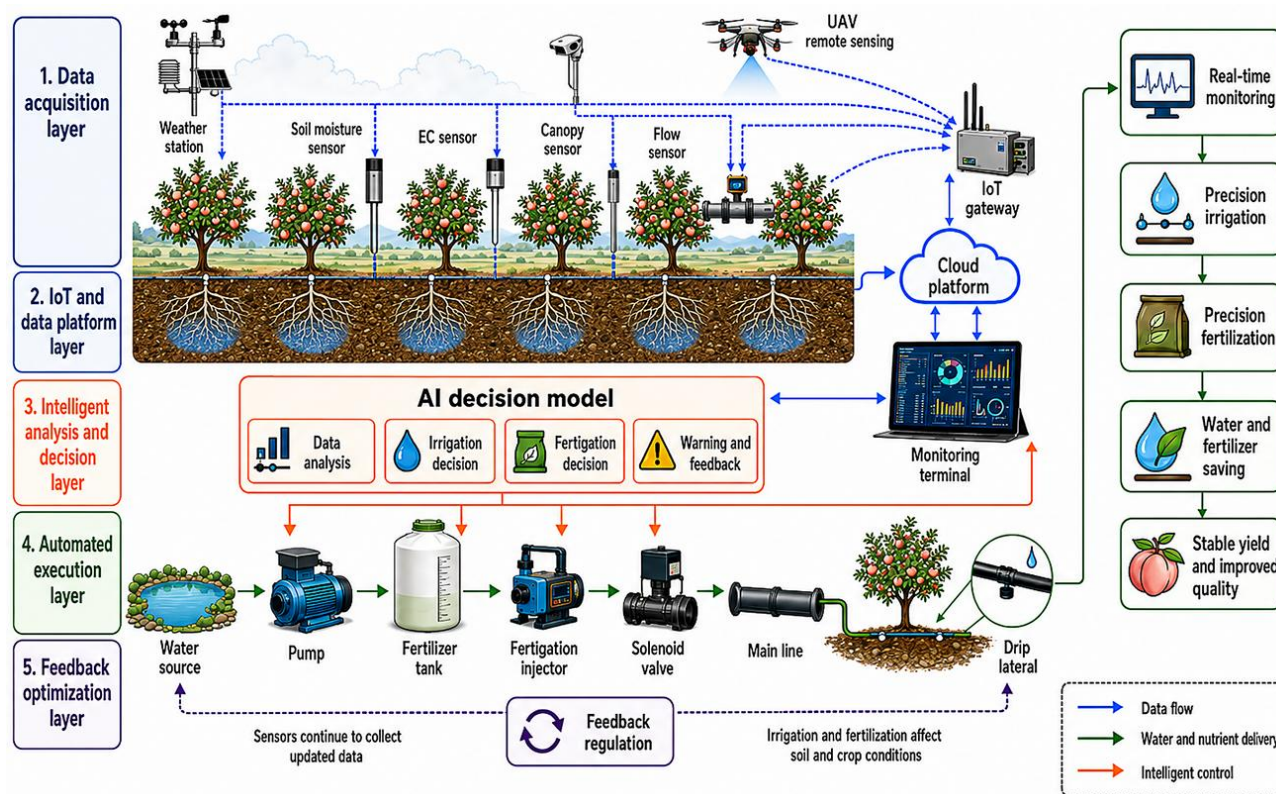


Figure 3 Smart orchard management system for precision irrigation and fertilization

Image caption: This system integrates sensors, UAV remote sensing, an IoT platform, and an AI decision model to achieve real-time monitoring, intelligent decision-making, automated execution, and feedback optimization of water and nutrient management in peach orchards, thereby improving resource use efficiency and promoting stable yield and improved fruit quality

8 Conclusions and Future Perspectives

Based on existing studies, high-yield and high-quality peach cultivation cannot be achieved simply by increasing fertilizer or irrigation inputs. Instead, it should be built on the coordinated regulation of water, nutrients, tree growth, and environmental conditions. Nitrogen, phosphorus, and potassium are key factors affecting peach yield and fruit quality, among which nitrogen regulation is particularly sensitive. Peach trees generally maintain better yield and fruit quality when leaf nitrogen content remains within an appropriate range and when phosphorus and potassium supplies are relatively balanced. If the interactions among nutrients are ignored, or if the influence of nutrient reserves from the previous year on current-year growth is not considered, fertilization decisions may become inaccurate, leading to nutrient imbalance, quality decline, or resource waste. Therefore, integrated water and fertilizer management in peach cultivation should shift from experience-based fertilization to precise regulation based on tree demand, soil nutrient supply, and target yield.

Under the background of climate change and water scarcity, irrigation optimization is of great significance for maintaining stable peach production. Proper water supply in young orchards is beneficial for canopy formation and later yield improvement. In mature orchards, techniques such as drip irrigation, regulated deficit irrigation, and partial root-zone drying can reduce water consumption while maintaining relatively stable yield. Integrated drip irrigation and fertilization can synchronously deliver water and nutrients to the active root zone, thereby improving water use efficiency and fertilizer uptake efficiency while reducing evaporation, deep percolation, and nutrient loss. This indicates that water management and nutrient management in peach cultivation should not be treated separately. Only through water-fertilizer coordination can resource use efficiency be improved.

In the future, peach water and fertilizer management will further develop toward intelligent and digitalized systems. Technologies such as thermal imaging, crop water stress index, stem water potential monitoring, satellite

multispectral data, and Internet of Things sensors can be used to evaluate tree water status and guide precise irrigation. Machine learning models can integrate meteorological, soil, tree, and remote sensing data to predict water demand, nutrient status, and changes in yield and fruit quality, thereby providing decision support for orchard management. Future research should strengthen the integration of sensor data, water-fertilizer management records, and nutrient diagnosis models, and develop peach-specific management tools suitable for different production regions, tree ages, and soil types.

From the perspective of production application, efficient peach cultivation should take integrated drip irrigation and fertilization as the core, combined with regulated deficit irrigation, soil mulching, microclimate regulation, and precise fertilization. The key is not to apply more water and fertilizer, but to ensure that water and nutrients are absorbed and utilized by trees at the appropriate time, location, and ratio. Future studies should also pay attention to soil salinity accumulation, microbial changes, nutrient residues, and environmental impacts under long-term application. A water and fertilizer integrated management system that balances high yield, high quality, water saving, fertilizer saving, and ecological safety should be gradually established, so as to promote the peach industry toward green and sustainable development.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Reference

- Abidi W., Akrimi R., Hajlaoui H., Rejeb H., and Gogorcena Y., 2023, Foliar fertilization of potassium silicon improved postharvest fruit quality of peach and nectarine [*Prunus persica* (L.) Batsch] cultivars, *Agriculture*, 13(1): 195.
<https://doi.org/10.3390/agriculture13010195>
- AboOgiela H.M.A., 2021, The effect of water shortage at different stages of fruit growth on the yield and fruit quality in, *Menoufia Journal of Plant Production*, 6(8): 389-403.
<https://doi.org/10.21608/mjppf.2021.193752>
- Abrisqueta J.M., Mounzer O., Álvarez S., Conejero W., García-Orellana Y., Tapia L.M., Vera J., Abrisqueta I., and Ruiz-Sánchez M., 2008, Root dynamics of peach trees submitted to partial rootzone drying and continuous deficit irrigation, *Agricultural Water Management*, 95(8): 959-967.
<https://doi.org/10.1016/j.agwat.2008.03.003>
- Ali M.A., Abd-Elmageed N.A., Abd-El Hady R.M., and Osman A., 2019a, Growth, yield, fruit quality and elemental composition as affected by some macronutrients fertilization of 'Florida Prince' peach cultivar, *Journal of the Advances in Agricultural Researches*, 24(3): 326-341.
<https://doi.org/10.21608/jalexu.2019.163450>
- Ali M.A., Ezz T.M., Abd El-Megeed N., and Felfil M., 2019b, Effect of foliar application with some micronutrients on 'Florida Prince' cultivar peach tree, *Journal of the Advances in Agricultural Researches*, 24(3): 410-425.
<https://doi.org/10.21608/jalexu.2019.163473>
- Ali N., Dong Y., and Lavelly E., 2024, Impact of irrigation scheduling on yield and water use efficiency of apples, peaches, and sweet cherries: A global meta-analysis, *Agricultural Water Management*, 306: 109148.
<https://doi.org/10.1016/j.agwat.2024.109148>
- Andrade D., Covarrubias M.P., Benedetto G., Pereira E.G., and Almeida A.M., 2019, Differential source-sink manipulation affects leaf carbohydrate and photosynthesis of early- and late-harvest nectarine varieties, *Theoretical and Experimental Plant Physiology*, 31(2): 341-356.
<https://doi.org/10.1007/s40626-019-00150-0>
- Anthony B.M., and Minas I.S., 2021, Optimizing peach tree canopy architecture for efficient light use, increased productivity and improved fruit quality, *Agronomy*, 11(10): 1961.
<https://doi.org/10.3390/agronomy11101961>
- Bai Q., Shen Y., and Huang Y., 2021, Advances in mineral nutrition transport and signal transduction in Rosaceae fruit quality and postharvest storage, *Frontiers in Plant Science*, 12: 620018.
<https://doi.org/10.3389/fpls.2021.620018>
- Bianco R.L., and Rieger M., 2002, Roles of sorbitol and sucrose in growth and respiration of 'Encore' peaches at the three developmental stages, *Journal of the American Society for Horticultural Science*, 127(2): 297-302.
<https://doi.org/10.21273/jashs.127.2.297>

- Bruno M., Piarulli M., Vitti C., Mastrangelo M., Azzolini A., Ciurlia A., Rana G., and Ferrara R., 2025, Mixed compost application: A sustainable tool for improving soil carbon dynamics in a peach orchard under Mediterranean conditions, *Sustainability*, 17(12): 5613.
<https://doi.org/10.3390/su17125613>
- Carrasco-Cuello F., Van der Heijden G., Rufat J., and Torres E., 2024, Unraveling calcium absorption and distribution in peach and nectarine during fruit development through ⁴⁴Ca isotope labeling, *Plants*, 13(16): 2287.
<https://doi.org/10.3390/plants13162287>
- Casamali B., van Iersel M.W., and Chavez D.J., 2021a, Plant growth and physiological responses to improved irrigation and fertilization management for young peach trees in the southeastern United States, *HortScience*, 56(3): 336-346.
<https://doi.org/10.21273/hortsci15505-20>
- Casamali B., van Iersel M.W., and Chavez D.J., 2021b, Nitrogen partitioning in young “Julyprince” peach trees grown with different irrigation and fertilization practices in the southeastern United States, *Agronomy*, 11(2): 350.
<https://doi.org/10.3390/agronomy11020350>
- Chawla R., and Kumar Sharma S., 2025, Nitrogen fertilization of stone fruits: A comprehensive review, *Journal of Plant Nutrition*, 48(3): 445-485.
<https://doi.org/10.1080/01904167.2024.2405990>
- Chen X., Yan X., Wang M., Cai Y., Weng X., Su D., Guo J., Wang W., Hou Y., Ye D., Zhang S.-H., Liu D., Tong L., Xu X., Zhou S., Wu L., and Zhang F., 2022, Long-term excessive phosphorus fertilization alters soil phosphorus fractions in the acidic soil of pomelo orchards, *Soil and Tillage Research*, 215: 105214.
<https://doi.org/10.1016/j.still.2021.105214>
- Dbara S., Lahmar K., and Ben Mimoun M., 2018, Potassium mineral nutrition combined with sustained deficit irrigation to improve yield and quality of a late season peach cultivar (*Prunus persica* L. cv ‘Chatos’), *International Journal of Fruit Science*, 18(4): 369-382.
<https://doi.org/10.1080/15538362.2018.1438329>
- Domínguez-Niño J.M., Oliver-Manera J., Girona J., and Casadesús J., 2020, Differential irrigation scheduling by an automated algorithm of water balance tuned by capacitance-type soil moisture sensors, *Agricultural Water Management*, 228: 105880.
<https://doi.org/10.1016/j.agwat.2019.105880>
- Faci J.M., Medina E.T., Martínez-Cob A., and Alonso J.M., 2014, Fruit yield and quality response of a late season peach orchard to different irrigation regimes in a semi-arid environment, *Agricultural Water Management*, 143: 102-112.
<https://doi.org/10.1016/j.agwat.2014.07.004>
- Fisk C.L., Parker M.L., and Mitchem W., 2015, Vegetation-free width and irrigation impact peach tree growth, fruit yield, fruit size, and incidence of hemipteran insect damage, *HortScience*, 50(5): 699-704.
<https://doi.org/10.21273/hortsci.50.5.699>
- Goldan E., Nedeff V., Bărsan N., Culea M., Panainte-Lehăduş M., Moşneguţu E., Tomozei C., Chiţimuş D., and Irimia O., 2023, Assessment of manure compost used as soil amendment—A review, *Processes*, 11(4): 1167.
<https://doi.org/10.3390/pr11041167>
- Hamza A.H., Menesi A., Aalaf A.H.E., Elbeltagi A., Elwakeel A.E., Salem A., Dewidar A., Taha M.F., El-Shinawy D.M., Eid M.H., Al-Othman A., and Fekry W., 2025, Influence of the magnetic field on the characteristics of sandy soil, groundwater, fruit quality, and peach water productivity at different irrigation distances in a desert environment, *Applied Water Science*, 15(9): 233.
<https://doi.org/10.1007/s13201-025-02593-0>
- Iglesias I., and Echeverría G., 2022, Current situation, trends and challenges for efficient and sustainable peach production, *Scientia Horticulturae*, 296: 110899.
<https://doi.org/10.1016/j.scienta.2022.110899>
- Katz L., Ben-Gal A., Litaor M., Naor A., Peres M., Peeters A., Alchanatis V., and Cohen Y., 2023, A spatiotemporal decision support protocol based on thermal imagery for variable rate drip irrigation of a peach orchard, *Irrigation Science*, 41(2): 215-233.
<https://doi.org/10.1007/s00271-022-00830-x>
- Kumar S., and Kaur G., 2021, Effect of integrated nutrient management on the fruit quality parameters and yield of peach (*Prunus persica* Batsch) cv. Shan-i-Punjab, *International Journal of Current Microbiology and Applied Sciences*, 10: 3250-3258.
<https://doi.org/10.20546/ijcmas.2021.1002.356>
- Laita M., Sabbahi R., Azzaoui K., Hammouti B., Nasri H., Messaoudi Z., Benkirane R., and Aithaddou H., 2024, Optimizing water use and crop yield with deficit irrigation techniques: A comprehensive overview and case study from Morocco, *Multidisciplinary Reviews*, 7(4): e2024074.
<https://doi.org/10.31893/multirev.2024074>
- Lawrence B.T., and Melgar J.C., 2023, Annual compost amendments can replace synthetic fertilizer, improve soil moisture, and ensure tree performance during peach orchard establishment in a humid subtropical climate, *Frontiers in Plant Science*, 14: 1172038.
<https://doi.org/10.3389/fpls.2023.1172038>
- Lawrence B.T., and Melgar J.C., 2024, Effect of municipal mulch and poultry litter amendments on soil and tree parameters of a mature peach orchard in a humid subtropical climate, *Journal of Soil Science and Plant Nutrition*, 24(2): 2469-2484.
<https://doi.org/10.1007/s42729-024-01666-4>
- Lesičar J., Šindrak Z., Šic Žlabur J., Voča S., and Skendrović Babojelić M., 2016, Influence of fruit thinning and summer pruning on the yield and fruit quality of peach cultivar ‘Royal Gem’, *Agriculturae Conspectus Scientificus*, 81(3): 155-159.

- Lesmes-Vesga R.A., Cano L.M., Ritenour M.A., Sarkhosh A., Chaparro J.X., and Rossi L., 2023, Variation in the root system architecture of peach × (peach × almond) backcrosses, *Plants*, 12(9): 1874.
<https://doi.org/10.3390/plants12091874>
- Li H., Mei X., Wang J., Huang F., Hao W., and Li B., 2021, Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China, *Agricultural Water Management*, 244: 106534.
<https://doi.org/10.1016/j.agwat.2020.106534>
- Liang R., Wang L., Wang X., Zhang J., and Gan X., 2023, Effects of exogenous ALA on leaf photosynthesis, photosynthate transport, and sugar accumulation in *Prunus persica* L., *Forests*, 14(4): 723.
<https://doi.org/10.3390/f14040723>
- Lou Y., Han Y., Miao Y., Shang H., Lv Z., Wang L., and Wang S., 2024, A study of the soil water potential threshold values to trigger irrigation of ‘Shimizu Hakuto’ peach at pivotal fruit developmental stages, *Horticultural Plant Journal*, 10(2): 376-386.
<https://doi.org/10.1016/j.hpj.2022.10.011>
- Maatallah S., Guizani M., Elloumi O., Montevicchi G., Antonelli A., Ghrab M., and Dabbou S., 2024, Yield and biochemical fruit quality of irrigated peach cultivars subjected to conventional farmer’s fertilization practices in warm production area, *Journal of Food Composition and Analysis*, 129: 106121.
<https://doi.org/10.1016/j.jfca.2024.106121>
- Maletsika P., Cavalaris C., Giouvanis V., and Nanos G.D., 2022, Effects of alternative fertilization and irrigation practices on the energy use and carbon footprint of canning peach orchards, *Sustainability*, 14(14): 8583.
<https://doi.org/10.3390/su14148583>
- Manganaris G.A., Minas I., Cirilli M., Torres R., Bassi D., and Costa G., 2022, Peach for the future: A specialty crop revisited, *Scientia Horticulturae*, 305: 111390.
<https://doi.org/10.1016/j.scienta.2022.111390>
- Mazzoni L., Medori I., Balducci F., Marcellini M., Acciarri P., Mezzetti B., and Capocasa F., 2022, Branch numbers and crop load combination effects on production and fruit quality of flat peach cultivars (*Prunus persica* (L.) Batsch) trained as Catalanian Vase, *Plants*, 11(3): 308.
<https://doi.org/10.3390/plants11030308>
- Melo G.W.B.D., Sete P.B., Ambrosini V.G., Freitas R.F., Basso A., and Brunetto G., 2016, Nutritional status, yield and composition of peach fruit subjected to the application of organic compost, *Acta Scientiarum. Agronomy*, 38(1): 103-109.
<https://doi.org/10.4025/actasciagron.v38i1.25638>
- Menegatti R.D., Souza A.D.G., and Bianchi V.J., 2021, Nutritional efficiency for nitrogen, phosphorus and potassium in peach rootstocks, *Journal of Plant Nutrition*, 44(2): 228-237.
<https://doi.org/10.1080/01904167.2020.1806306>
- Mirás-Avalos J.M., Pérez-Sarmiento F., Alcobendas R., Alarcón J.J., Mounzer O., and Nicolás E., 2016, Using midday stem water potential for scheduling deficit irrigation in mid-late maturing peach trees under Mediterranean conditions, *Irrigation Science*, 34(2): 161-173.
<https://doi.org/10.1007/s00271-016-0493-9>
- Morandi B., Corelli Grappadelli L., Rieger M., and Lo Bianco R., 2008, Carbohydrate availability affects growth and metabolism in peach fruit, *Physiologia Plantarum*, 133(2): 229-241.
<https://doi.org/10.1111/j.1399-3054.2008.01068.x>
- Mosie T., Seleshi G., and Setu H., 2025, Yield and fruit quality of peach (*Prunus persica* L.) var. “Tropic Beauty” as affected by intra-row spacing and nitrogen-phosphorus-sulfur blend fertilizer rate, *Discover Sustainability*, 6: e01738.
<https://doi.org/10.1007/s43621-025-01738-0>
- Muradi B., and Godara A.K., 2020, Effect of foliar fertilization of boron, zinc and iron on fruit quality and leaf nutrients content of peach cv. Shan-e-Punjab, *Current Journal of Applied Science and Technology*, 39(1): 43-51.
<https://doi.org/10.9734/cjast/2020/v39i130479>
- Nava G., Júnior R.C., Parent L., Brunetto G., Moura-Bueno J.M., Navroski R., Benati J.A., and Barreto C.F., 2022, Esmeralda peach (*Prunus persica*) fruit yield and quality response to nitrogen fertilization, *Plants*, 11(3): 352.
<https://doi.org/10.3390/plants11030352>
- Oldoni H., Terra V.S.S., Timm L.C., Júnior C.R., and Monteiro A.B., 2019, Delineation of management zones in a peach orchard using multivariate and geostatistical analyses, *Soil and Tillage Research*, 191: 1-10.
<https://doi.org/10.1016/j.still.2019.03.008>
- Oran R.B., Koşar D.A., Demirsoy H., and Ertürk Ü., 2024, The training systems affect fruit quality, yield, and labor efficiency in peach (*P. persica* L. Batsch), *HortScience*, 59(8): 1172-1181.
<https://doi.org/10.21273/hortsci17961-24>
- Park J.M., Lee S.E., Lim T.J., and Noh J.S., 2013, Effect of slurry composting biofiltration (SCB) liquid manure on shoot growth and fruit qualities of peach (*Prunus persica* L.) and soil chemical properties in orchard, *Korean Journal of Soil Science and Fertilizer*, 46(6): 530-535.
<https://doi.org/10.7745/kjssf.2013.46.6.530>
- Pascual M., Villar J.M., and Rufat J., 2016, Water use efficiency in peach trees over a four-years experiment on the effects of irrigation and nitrogen application, *Agricultural Water Management*, 164: 253-266.
<https://doi.org/10.1016/j.agwat.2015.10.021>

- Rahmati M., Davarynejad G.H., Génard M., Bannayan M., Azizi M., and Vercambre G., 2015, Peach water relations, gas exchange, growth and shoot mortality under water deficit in semi-arid weather conditions, *PLoS One*, 10(4): e0120246.
<https://doi.org/10.1371/journal.pone.0120246>
- Razouk R., Kajji A., Hamdani A., Charafi J., Hssaini L., and Bouda S., 2021, Yield and fruit quality of almond, peach and plum under regulated deficit irrigation, *Engineering Agriculture*, 8(4): 583-593.
<https://doi.org/10.15302/j-fase-2020325>
- Saraginovski N., and Kiprijanovski M., 2021, The effect of the short pruning on the yield and quality of the fruits at the peach tree, *Horticultural Science*, 48(2).
<https://doi.org/10.17221/158/2019-hortsci>
- Sharma K., Sharma J.C., Sharma S., Sharma N., Sharma R., Hashem A., Almutairi K.F., and Abd_Allah E.F., 2024, Optimizing leaf nutrient status, growth, and yield parameters in high-density apple orchards (cv. Super Chief) via integrated drip irrigation and fertigation techniques, *Heliyon*, 10(16).
<https://doi.org/10.1016/j.heliyon.2024.e36136>
- Song K., Qin Q., Yang Y.-F., Sun L.-J., Sun Y.-F., Zheng X.-Q., Lv W., and Xue Y., 2023, Drip fertigation and plant hedgerows significantly reduce nitrogen and phosphorus losses and maintain high fruit yields in intensive orchards, *Journal of Integrative Agriculture*, 22(2): 598-610.
<https://doi.org/10.1016/j.jia.2022.08.008>
- Souza A.D.G., Ritterbusch C.W., Menegatti R.D., Smiderle O.J., and Bianchi V.J., 2019, Nutritional efficiency and morphophysiological aspects with growth in the 'Okinawa Roxo' peach rootstock, *Journal of Agricultural Science*, 11(9): 1-13.
<https://doi.org/10.5539/jas.v11n9p221>
- Strooboscher Z.J., Athelley A., and Guzmán S.M., 2024, Assessing capacitance soil moisture sensor probes' ability to sense nitrogen, phosphorus, and potassium using volumetric ion content, *Frontiers in Agronomy*, 6: 1346946.
<https://doi.org/10.3389/fagro.2024.1346946>
- Sun H., Huang X., Chen T., Zhou P., Huang X., Jin W., Liu D., Zhang H., Zhou J., Wang Z., Hayat F., and Gao Z., 2022a, Fruit quality prediction based on soil mineral element content in peach orchard, *Food Science & Nutrition*, 10(6): 1756-1767.
<https://doi.org/10.1002/fsn3.2794>
- Sun M., Liu X., Shi K., Peng F., and Xiao Y., 2022b, Effects of root zone aeration on soil microbes species in a peach tree rhizosphere and root growth, *Microorganisms*, 10(10): 1879.
<https://doi.org/10.3390/microorganisms10101879>
- Thakur S., Sinha A., and Ghosh Bag A., 2023, Boron—a critical element for fruit nutrition, *Communications in Soil Science and Plant Analysis*, 54(21): 2899-2914.
<https://doi.org/10.1080/00103624.2023.2252878>
- Tirado-Corbalá R., Román-Paoli E., and Muñoz-Barreto J., 2021, Fertilization and precise irrigation scheduling for mature avocado, *Journal of Agriculture of the University of Puerto Rico*: 1-2.
<https://doi.org/10.46429/jaupr.v105i1.19637>
- Toumi I., Ghrab M., Zarrouk O., and Nagaz K., 2024, Impact of deficit irrigation strategies using saline water on soil and peach tree yield in an arid region of Tunisia, *Agriculture*, 14(3): 377.
<https://doi.org/10.3390/agriculture14030377>
- Toumi I., Zarrouk O., Ghrab M., and Nagaz K., 2022, Improving peach fruit quality traits using deficit irrigation strategies in southern Tunisia arid area, *Plants*, 11(13): 1656.
<https://doi.org/10.3390/plants11131656>
- Tsoumanis D., Katsenios N., and Monokrousos N., 2025, Enhancing peach tree fertilization: Investigating *Methylobacterium symbioticum* SB23 as game-changing agent, *Agronomy*, 15(3): 521.
<https://doi.org/10.3390/agronomy15030521>
- Wang D., Zhang H., and Gartung J., 2020, Long-term productivity of early season peach trees under different irrigation methods and postharvest deficit irrigation, *Agricultural Water Management*, 230: 105940.
<https://doi.org/10.1016/j.agwat.2019.105940>
- Wang Y.M., and Wang P.C., 2016, Effect of organic compost mulching on orchard soil property, *Chemical Engineering Transactions*, 55: 379-384.
<https://doi.org/10.3303/cet1655064>
- Wei Q., Xu J., Liu Y., Wang D., Chen S., Qian W., He M., Chen P., Zhou X., and Qi Z., 2024, Nitrogen losses from soil as affected by water and fertilizer management under drip irrigation: Development, hotspots and future perspectives, *Agricultural Water Management*, 296: 108791.
<https://doi.org/10.1016/j.agwat.2024.108791>
- Xiao Y., Peng F., Zhang Y., Wang J., Zhuge Y., Zhang S., and Gao H., 2019, Effect of bag-controlled release fertilizer on nitrogen loss, greenhouse gas emissions, and nitrogen applied amount in peach production, *Journal of Cleaner Production*, 234: 258-274.
<https://doi.org/10.1016/j.jclepro.2019.06.219>
- Yang G., Kang J., Wang Y., Zhao X., and Wang S., 2024, Environmental transport of excess nitrogen fertilizer in peach orchard: Evidence arising from ¹⁵N tracing trial, *Agriculture, Ecosystems & Environment*, 370: 109066.
<https://doi.org/10.1016/j.agee.2024.109066>

- Yang G., Wang Y., Wang S., and Zhao X., 2023, Drilling of super large granular slow-release humic acid compound fertilizer improves simultaneously environmental and economic benefits in peach orchard, *Agriculture, Ecosystems & Environment*, 348: 108437.
<https://doi.org/10.1016/j.agee.2023.108437>
- Yuan Q., Qi Y., Huang K., Sun Y., Wang W., and Lyu X., 2024, Research progress in intelligent diagnosis key technology for orchard nutrients, *Applied Sciences*, 14(11): 4744.
<https://doi.org/10.3390/app14114744>
- Zambrano-Vaca C., Zotarelli L., Beeson Jr R.C., Morgan K.T., Migliaccio K.W., Chaparro J.X., and Olmstead M.A., 2020, Determining water requirements for young peach trees in a humid subtropical climate, *Agricultural Water Management*, 233: 106102.
<https://doi.org/10.1016/j.agwat.2020.106102>
- Zayan M.A., Mikhael G.B., and Okba S.K., 2016, Treatments for improving tree growth, yield and fruit quality and for reducing double fruit and deep suture incidence in “Desert Red” peach trees, *International Journal of Horticultural Science*, 22(3-4): 7-19.
<https://doi.org/10.31421/ijhs/22/3-4/1187>
- Zhang B., Chen H., Zhang Y., Guo S., Wang X., Sun M., Yu M., and R., 2024, Effects of blooming and fruit thinning on the yield, fruit quality, and leaf photosynthesis of peach cultivar ‘Xiahui 5’ in China, *Food Quality and Safety*, 8: fyae019.
<https://doi.org/10.1093/fqsafe/fyae019>
- Zhang H., Wang D., and Gartung J.L., 2017, Influence of irrigation scheduling using thermometry on peach tree water status and yield under different irrigation systems, *Agronomy*, 7(1): 12.
<https://doi.org/10.3390/agronomy7010012>
- Zhang Y., Guo J., Ren F., Jiang Q., Zhou X., Zhao J., and Liu X., 2022, Integrated physiological, transcriptomic, and metabolomic analyses of the response of peach to nitrogen levels during different growth stages, *International Journal of Molecular Sciences*, 23(18): 10876.
<https://doi.org/10.3390/ijms231810876>
- Zhang Z.L., Liu G.D., Zhang F.C., Zheng C.X., Ni F.Q., Kang Y.H., and Zeng Y., 2014, Effects of nitrogen content on growth and hydraulic characteristics of peach (*Prunus persica* L.) seedlings under different soil moisture conditions, *Journal of Forestry Research*, 25(2): 365-375.
<https://doi.org/10.1007/s11676-014-0464-z>
- Zhou H., Zhang F., Roger K., Wu L.-F., Gong D., Na Z., Dongxue Y., Xiang Y., and Li Z.-J., 2017, Peach yield and fruit quality is maintained under mild deficit irrigation in semi-arid China, *Journal of Integrative Agriculture*, 16: 1173-1183.
[https://doi.org/10.1016/s2095-3119\(16\)61571-x](https://doi.org/10.1016/s2095-3119(16)61571-x)

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Research Insight

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Nutrient Management for Enhancing Sweet Cherry Fruit Firmness and Shelf Life

Shaomin Yang¹, Shiyong Yu² ✉¹ Hainan Institute of Biotechnology, Haikou, 570206, Hainan, China² Biotechnology Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, China✉ Corresponding author: shiyong.yu@cuixi.orgInternational Journal of Horticulture, 2026, Vol.16, No.3 doi: [10.5376/ijh.2026.16.0017](https://doi.org/10.5376/ijh.2026.16.0017)

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Abstract Sweet cherry fruit are prone to softening, water loss, cracking, and decay after harvest, resulting in a short shelf life. Fruit firmness and storability directly affect commercial grading and market value. This study analyzes the improvement of sweet cherry fruit firmness and storage quality through nutrient management, focusing on the effects of key nutrients such as calcium, potassium, magnesium, and boron on cell wall stability, membrane integrity, and postharvest senescence, and proposes practical management strategies for production. The results indicate that calcium is the core element for maintaining fruit firmness and delaying softening. It can enhance calcium-pectate cross-linking, stabilize cell wall and membrane structures, and reduce the risks of cracking, decay, and weight loss. However, calcium uptake is restricted by fruit developmental stage, declining xylem function, and cultivar differences. Potassium promotes fruit enlargement, sugar accumulation, and ripening, but excessive application may increase the K:Ca ratio and weaken firmness retention. Magnesium improves fruit quality mainly by promoting photosynthesis and carbon assimilation, while boron participates in cell wall formation, fruit set, and calcium distribution. This study suggests that supplementation with a single nutrient is unlikely to consistently improve the storability of sweet cherry fruit. A stage-specific nutrient management model integrating early calcium supply, boron supplementation at flowering, moderate potassium and magnesium regulation, nitrogen control, and postharvest calcium treatment should therefore be established.

Keywords Sweet cherry (*Prunus avium* L.); Nutrient management; Fruit firmness; Calcium management; Shelf life; Postharvest preservation

1 Introduction

Sweet cherry (*Prunus avium* L.) is an important high-value horticultural crop with strong commercial relevance in the fresh-fruit market. Consumers generally evaluate its quality according to fruit appearance, flavor, texture, and nutritional value, among which fruit size, color, firmness, and freshness directly affect market grading and selling price (Correia et al., 2017; Çolak et al., 2025). Because sweet cherry has a concentrated harvest period, a short shelf life, and high requirements for maintaining class I fruit quality during distribution, its commercial competitiveness depends not only on yield but also on the stability of fruit quality during picking, grading, packaging, storage, and transportation (Ivanova et al., 2023). However, sweet cherry is a typical highly perishable fresh fruit. After harvest, it is prone to flesh softening, water loss, decay, and mechanical injury, which shorten shelf life and restrict long-distance transportation (Chockchaisawasdee et al., 2016; Çolak et al., 2025). Among these quality attributes, fruit firmness is particularly important. Firmer fruit can better withstand external damage during postharvest handling and logistics, while also meeting consumer demand for a crisp and tender texture (Blanco et al., 2021). Previous studies have shown that cherry firmness usually decreases continuously during storage, accompanied by changes in acidity, soluble solids balance, and other quality indices, ultimately affecting commercial life and market value (Blanco et al., 2021; Beinsan et al., 2025; Xing et al., 2025).

Sweet cherry fruit have a short developmental period, usually requiring only 60–80 days from bloom to harvest. During this stage, fruit compete strongly with vegetative organs such as leaves and shoots for carbohydrates and mineral nutrients. Therefore, source–sink relationships and nutrient supply have important effects on final fruit quality (Matteo et al., 2022; Santos et al., 2024). Appropriate crop load, sufficient assimilate supply, and suitable

mineral nutrition levels help promote fruit enlargement, sugar and acid accumulation, and tissue structure formation. In contrast, source limitation or nutrient imbalance during fruit development may lead to smaller fruit, reduced flavor, and softer texture (Quiroz et al., 2023). Thus, nutrient management is not only related to tree growth and yield formation, but also directly involved in fruit cell wall construction, membrane system stability, and the development of postharvest resistance to deterioration.

Among the mineral elements affecting cherry firmness and storability, calcium, potassium, and magnesium have received considerable attention. Calcium can bind to cell wall components such as pectin and cellulose, strengthen cell wall stability, and participate in the regulation of membrane permeability and stress signaling. It is therefore closely associated with flesh tissue rigidity and resistance to softening (Varaldo and Giacalone, 2025). Potassium is one of the most abundant macronutrients in cherry fruit and is associated with fruit size, soluble solids, maturity progression, and changes in firmness (Ateş et al., 2022; Santos et al., 2024). Magnesium indirectly affects fruit quality formation by participating in photosynthesis, carbon metabolism, and various enzymatic reactions. In recent years, foliar nutrient application has been regarded as an important measure for rapidly regulating fruit mineral composition, alleviating nutrient deficiencies under field conditions, and improving postharvest quality (Santos et al., 2024).

Existing studies have shown that preharvest spraying or postharvest calcium treatment can, to some extent, improve cherry firmness, reduce weight loss, decrease decay incidence, and alleviate pedicel shriveling. However, these effects are often influenced by cultivar, environment, fruit developmental stage, and the efficiency of calcium uptake and transport (Belge et al., 2017; Winkler and Knoche, 2019). Calcium supplementation during early fruit development may be more favorable for calcium entry into the fruit and its participation in cell wall structure formation. As fruit expand rapidly, however, declining calcium concentration and restricted late-stage calcium import may weaken its regulatory effect (Matteo et al., 2022). The proportional relationship among mineral elements should also not be overlooked. Studies have shown that fruit firmness is positively correlated with calcium content but negatively correlated with K:Ca and N:Ca ratios, indicating that simply increasing the supply of a single element does not necessarily lead to stable quality improvement (Blanco et al., 2021; Quiroz et al., 2023). For example, potassium fertilization can help increase fruit weight, soluble solids, and some quality attributes, but excessive potassium supply may also reduce fruit calcium and magnesium concentrations, thereby affecting firmness retention (Ateş et al., 2022). Preharvest treatments with nutritional or metabolic regulatory functions, such as arginine and prohexadione-calcium, have also been reported to improve fruit firmness and storage quality, further suggesting that preharvest nutritional physiology influences postharvest performance (Pakkish and Mohammadrezakhani, 2022).

This study focuses on calcium, potassium, magnesium, and related nutrient regulation measures, and discusses their effects on structural development, firmness retention, and postharvest longevity of cherry fruit. It further explores practical strategies such as balanced fertilization, foliar nutrient supplementation, nutrient ratio adjustment, and synchronized nutrient supply during critical developmental stages. By emphasizing multi-element coordination and integrated preharvest–postharvest management, this study may provide a theoretical basis and practical reference for improving cherry fruit firmness, reducing storage losses, and enhancing commercial value.

2 Physiological Basis of Cherry Firmness and Shelf Life

2.1 Formation of firmness

Cherry fruit firmness arises from the combined effects of cell wall strength, middle lamella adhesion, and cell turgor (Figure 1). In fleshy fruits, firmness is determined by the mechanical properties of parenchyma cell walls and the extent of adhesion between adjacent cells, with tissue strength declining when these properties are modified during ripening (Posé et al., 2019; Wang et al., 2023). In sweet cherry, firmness is closely tied to storability and resistance to mechanical injury during handling, which is why firmer fruit better tolerate packing and transport (Correia et al., 2017; Matteo et al., 2022). Differences in mechanical behavior among cherry

cultivars are also explained in part by physical and chemical differences in the cell wall, linking tissue mechanics directly to wall composition (Matteo et al., 2022).

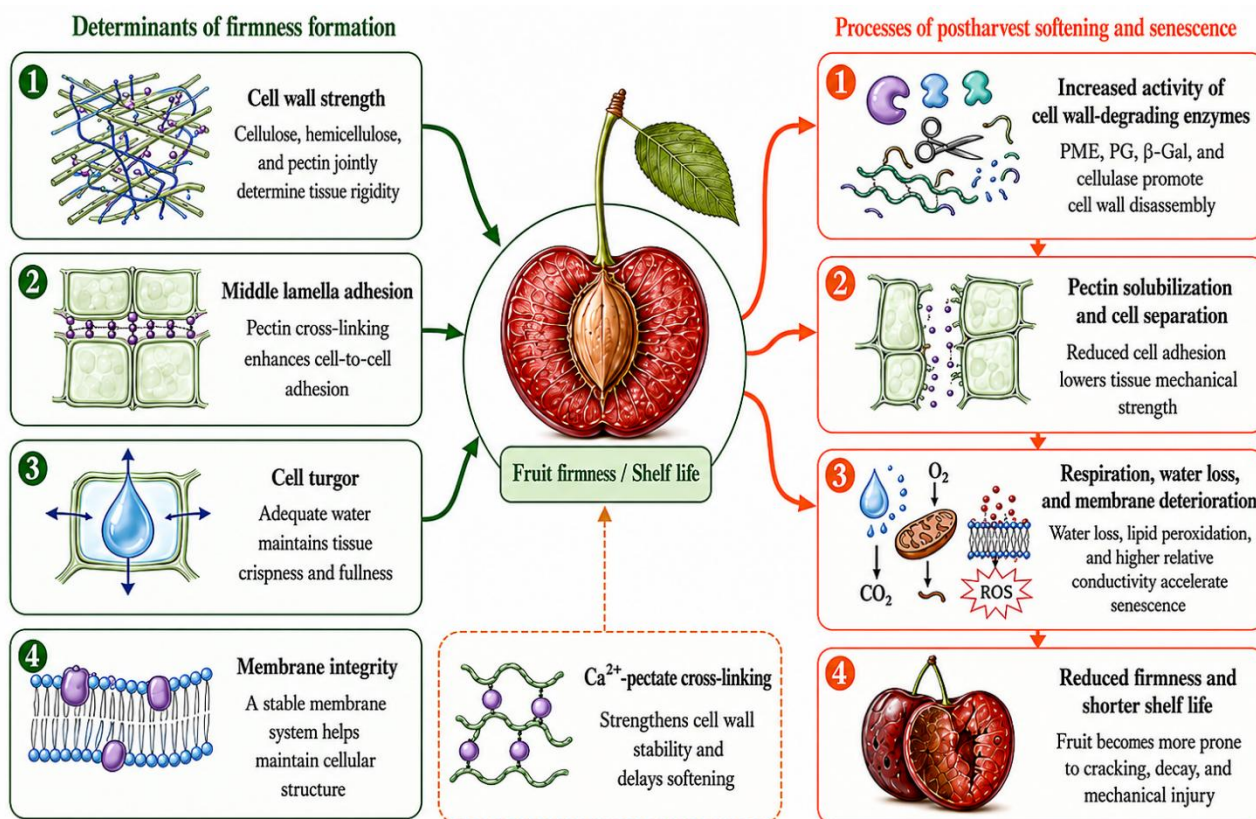


Figure 1 Physiological mechanisms underlying firmness formation and postharvest softening in sweet cherry fruit

Image caption: Fruit firmness is mainly determined by cell wall strength, middle lamella adhesion, cell turgor, and membrane integrity. During storage, cell wall-degrading enzymes promote pectin solubilization and polysaccharide disassembly, while respiration, water loss, and membrane deterioration accelerate firmness loss and senescence

At the structural level, the primary cell wall consists mainly of cellulose microfibrils embedded in a matrix of pectins and hemicelluloses, and this composite architecture underpins tissue rigidity (Hocking et al., 2016; Zhai et al., 2021). Pectin, cellulose, and hemicellulose are the major wall polysaccharides that change during ripening and softening (Guo et al., 2023; Wang et al., 2023). Pectin is especially important because it can account for a large fraction of fruit wall mass and contributes strongly to intercellular adhesion through the middle lamella (Matteo et al., 2022). Cellulose provides a comparatively stable structural scaffold, while hemicellulose helps connect the wall matrix; in cherry and related fruits, higher cellulose and hemicellulose contents are associated with firmer texture (Wang et al., 2023). Pectin solubilization and hemicellulose degradation appear to be especially important in determining firmness differences between hard- and soft-fleshed cherry types (Posé et al., 2019).

2.2 Postharvest softening and senescence

Postharvest softening is a major determinant of shelf life because it is an irreversible ripening outcome that reduces market quality after harvest (Zhai et al., 2021; Wang et al., 2025). The central mechanism is cell wall disassembly. During ripening and storage, pectins and matrix glycans are depolymerized and solubilized, neutral sugars are lost from pectin side chains, and intercellular adhesion weakens, which together increase cell separation and reduce firmness (Posé et al., 2019). In cherries, softening is associated with increased activities of pectin methylesterase, polygalacturonase, β -galactosidase, and related enzymes that damage cell wall components during storage (Correia et al., 2017). Xyloglucan endotransglucosylase/hydrolases, expansins, cellulases, and

polygalacturonases also participate in coordinated wall loosening by acting on hemicellulose, cellulose, and pectin networks (Zhai et al., 2021; Su et al., 2023).

Softening during storage is also driven by respiration, water loss, and membrane deterioration. Sweet cherries have a high respiration rate, and postharvest dehydration contributes directly to softening and senescence (Correia et al., 2017; Çolak et al., 2025). Weight loss rises substantially during cold storage as tissue moisture declines, and this mass loss reflects the combined effects of water loss and respiration (Çolak et al., 2025). Water loss is aggravated by the fruit's thin peel and depends partly on cuticle integrity, since the cuticle limits permeability, infections, and firmness loss (Wang et al., 2025; Çolak et al., 2025). Reduced turgor further accelerates texture loss, and membrane deterioration during storage is reflected by higher malondialdehyde and relative conductivity, both of which are reduced by calcium treatments (Wu et al., 2023; Wang et al., 2025).

2.3 Nutrient-dependent processes

Among nutrients, calcium has the clearest physiological role in maintaining firmness. Calcium cross-links de-esterified homogalacturonan to form calcium-pectate gels, increasing wall stiffness and strengthening cell-to-cell adhesion in the middle lamella (Guo et al., 2023). More broadly, calcium influences cell wall properties, membrane stability, water relations, and ripening-related signaling, so low fruit calcium can promote leaky membranes, irregular softening, and poorer storage behavior (Hocking et al., 2016). In sweet cherry, calcium-treated fruit were firmer and showed lower weight loss and decay incidence during storage, while foliar calcium also improved tissue rheological properties and reduced respiration (Belge et al., 2017; Matteo et al., 2022; Michailidis et al., 2022). Calcium effects are partly explained by reduced wall degradation, since calcium can inhibit pectin degradation and suppress the activity or expression of softening-related enzymes and genes (Matteo et al., 2022). Calcium import into cherry fruit declines as development progresses because xylem functionality is progressively lost, which helps explain why early-season calcium supply is often more effective than late applications (Winkler et al., 2020; Matteo et al., 2022).

Potassium and carbohydrate status also shape fruit texture, but their effects are more conditional than those of calcium. Carbohydrate availability during fruit development is required for high-quality sweet cherry, and altered phloem transport can produce larger and sweeter fruit that are nevertheless softer when calcium concentration declines and K:Ca and N:Ca ratios rise (Quiroz et al., 2023). Fruit firmness is positively related to calcium concentration and negatively related to K:Ca and N:Ca ratios, indicating that nutrient balance matters as much as absolute potassium supply. This is consistent with production studies showing that fruit grown under high tunnels had lower calcium, higher K:Ca ratios, and lower firmness. At the same time, potassium fertilization can improve firmness and nutrient content, and potassium is widely associated with fruit quality traits such as size, soluble solids, and maturity (Winkler et al., 2020).

3 Key Nutrients Affecting Cherry Fruit Firmness

3.1 Calcium management for firmness enhancement

Calcium management is central to firmness enhancement because calcium accumulation in fruit is closely tied to water delivery, apoplastic transport, and cell wall binding. Fruit calcium distribution depends strongly on water flow and apoplasmic interactions, and localized deficiencies can arise from differences in xylem structure, water relations, and pectin composition (Hocking et al., 2016). In sweet cherry, natural calcium concentration tends to decline during fruit development, indicating that calcium import slows while ongoing fruit enlargement dilutes accumulated calcium (Matteo et al., 2022). Foliar uptake remains possible after fruit set, but timing matters: early applications are generally more effective because young fruit stomata are functional, whereas later uptake increasingly occurs through the epidermis and the pedicel–fruit junction. Evidence from ‘Santina’ also suggests that firmness increases as calcium mass per fruit rises to about 1.3 mg, after which additional calcium shows little further firmness benefit, implying a threshold rather than a linear response (Blanco et al., 2021).

Calcium enhances firmness primarily by strengthening the cell wall and limiting softening processes. Ca^{2+} cross-links pectic polymers, helps form cell wall networks, increases mechanical strength, and can restrict the access of wall-degrading hydrolases (Hocking et al., 2016; Wu et al., 2023). In cherry systems, calcium treatments consistently retard firmness loss and postharvest deterioration: calcium-treated ‘Celeste’ fruit were firmer and had lower weight loss and decay than controls, while calcium-treated sweet cherries in cold storage maintained firmness and showed lower respiration (Belge et al., 2017; Erbaş and Koyuncu, 2021). Mechanistically, exogenous calcium reduces the activity or expression of softening-related enzymes and genes, including pectin methylesterase, polygalacturonase, cellulase, β -galactosidase, and expansin-associated pathways (Jaime-Guerrero et al., 2024). Calcium also helps reduce cracking because stronger and less rupture-prone cell walls better withstand excessive water uptake, and preharvest or postharvest calcium applications have been associated with lower cracking incidence in cherries (Matteo et al., 2022; Varaldo and Giacalone, 2025).

3.2 Potassium and magnesium regulation

Potassium and magnesium regulate cherry quality through complementary effects on growth, carbohydrate economy, and mineral balance. Potassium is the most abundant mineral element in sweet cherry fruit, often exceeding 4 500 mg/kg, and functions as a major osmotic solute that supports cell expansion, stomatal activity, photosynthesis, protein synthesis, and energy metabolism (Zhang et al., 2025). Because of these functions, potassium is closely linked to fruit size and sugar movement; recent work describes it as vital for increasing fruit size, soluble solids, color development, maturity advance, and yield (Erbaş and Koyuncu, 2021). Foliar potassium-based programs in sweet cherry have increased the proportion of marketable large fruit and improved storage firmness, while broader fertilizer studies associate potassium application with increased fruit length, fruit weight, and flesh firmness (Varaldo and Giacalone, 2025). However, potassium effects on firmness are not independent of calcium status. In ‘Santina’, fruit firmness was negatively correlated with the K:Ca ratio, and fruit grown under tunnels had both higher K:Ca and lower firmness, indicating that excessive potassium relative to calcium can weaken the firmness advantage otherwise gained from growth promotion (Blanco et al., 2021).

Magnesium supports firmness more indirectly through its role in photosynthesis and assimilate supply. Magnesium is a component of phytin, pectin, and many enzymes, and it contributes to the transport of both K^+ and Ca^{2+} within plant tissues (Zhang et al., 2025). It is also one of the principal characteristic mineral elements identified in sweet cherry fruit and is required for secondary metabolism and overall plant function (Zhang et al., 2025). By sustaining chlorophyll function, carbon assimilation, and carbohydrate production, magnesium helps maintain the assimilate supply needed for fruit growth and compositional quality. Recent foliar nutrition studies reported that magnesium treatments, particularly moderate-to-high rates, produced sweeter cherries and enhanced color development, consistent with a role in supporting source activity and sugar accumulation (Sandilya et al., 2023; Usmani et al., 2025). Even so, magnesium balance matters: the Mg:Ca ratio was negatively related to firmness in ‘Santina’, which indicates that beneficial magnesium effects on plant physiology do not substitute for adequate calcium in firm fruit tissues (Blanco et al., 2021).

3.3 Micronutrients related to tissue strength

Micronutrients contribute to tissue strength mainly through boron-mediated cell wall stabilization and through zinc- and manganese-dependent enzyme systems. Boron is particularly important because most plant boron is located in the cell wall, where it plays a major role in cell wall formation and mechanical strength (Thakur et al., 2023; Álvarez-Herrera et al., 2025). Boron is also functionally linked with calcium. It interacts with calcium and other nutrients, and boron deficiency can hinder calcium allocation to the tree canopy and edible fruit tissues (Vera-Maldonado et al., 2024). More broadly, boron influences uptake, absorption, and accumulation processes and is slightly mobile in the phloem, which helps explain why deficiency in rapidly growing tissues can disrupt fruit quality (Thakur et al., 2023). In sweet cherry, preflowering boron application increased endogenous boron content at early growth stages, improved fruit set, and promoted mesocarp cell enlargement, indicating that boron supports structural fruit development from the start of the season (Michailidis et al., 2023). Boron also delays

softening by reducing cell wall enzyme activities and limiting the transfer of wall-bound boron away from structural compartments, thereby helping maintain firmness during postharvest life (Álvarez-Herrera et al., 2025).

Zinc and manganese are less directly studied in cherry firmness than calcium or boron, but the available evidence supports roles in enzyme activity, photosynthesis, and fruit development. Boron-centered reviews identify both Zn and Mn among the essential micronutrients that interact with boron in plant nutritional networks, with the cell wall acting as an important intermediary of these interactions (Long and Peng, 2023). Zn homeostasis is linked to transporter regulation, root development, and optimized uptake, while Mn homeostasis is linked to transporter regulation and chlorophyll production, which is essential for photosynthesis (Usmani et al., 2025). In sweet cherry fruit, Zn and Mn are consistently present at low but measurable concentrations, typically within the broader 0.45–19 mg/kg range reported for Zn, Mn, B, Fe, Cu, and Na, which indicates that they are regular components of the fruit mineral matrix rather than incidental contaminants (Zhang et al., 2025). Practical evidence from fruit crops further suggests that combined micronutrient programs can improve fruit growth and quality traits, and cherry-focused work has cited positive effects of adding microelements such as B, Fe, and Zn to calcium-based spray programs for cracking management (Matteo et al., 2022; Sandilya et al., 2023).

Calcium remains the primary nutrient for direct firmness retention in cherry, while potassium, magnesium, boron, zinc, and manganese influence firmness and shelf life through growth, assimilate supply, and mineral balance. The most effective orchard strategy appears to be balanced, stage-specific nutrient management that increases fruit calcium while avoiding antagonistic nutrient ratios and supporting overall fruit development.

4 Nutrient Management Strategies During Cherry Fruit Development

4.1 Pre-bloom and bloom-stage nutrition

Early-season nutrition determines reproductive success because flower viability, fruit set, and the initial sink strength of young fruit are established around bloom, when cherry is highly sensitive to environmental and nutritional constraints (Xu et al., 2023). Pre-bloom nutrient programs should therefore prioritize adequate reserves and timely supply of nutrients linked to reproductive development, especially boron and calcium, while maintaining sufficient leaf support for carbohydrate supply to developing flowers and fruitlets (Figure 2) (Matteo et al., 2022; Bons and Sharma, 2023).

Fruit set depends on both reproductive nutrition and source–sink balance. In sweet cherry, high crop load is negatively associated with fruit quality, while regulation of fruit set alters leaf:fruit ratio and assimilate availability to the remaining fruitlets (Parveze et al., 2024). Boron is especially important at this stage because deficiency reduces fruit set in sweet cherry, and preflowering boron supply increases endogenous boron during early growth, improves fruit set, and promotes mesocarp cell enlargement (Michailidis et al., 2023; Arredondo et al., 2024). Not all bloom-stage B interventions are beneficial under all conditions, however, since a 0.01% boric acid spray reduced fruit set in one frost-prone field study, indicating that bloom applications require careful context-specific management rather than routine use (Xu et al., 2023).

Early calcium supply is physiologically justified because mineral influx into cherry fruit is fastest during early development, when xylem flow still dominates, whereas xylem functionality declines later toward maturity (Winkler et al., 2020; Michailidis et al., 2021). Calcium applied during dormancy can enter dormant flower buds and phloem, and high-dose dormant applications improved later fruit calcium status, cracking incidence, and fruit set (Michailidis et al., 2021). Boron supplementation is also effective when targeted early: soil-applied ^{10}B at full bloom was absorbed more strongly than pre-senescence application, whereas boron applied directly to flowers remained largely in the fruit, making floral boron a useful complementary method to support current-season fruit demand (Arredondo et al., 2024). Evidence from other fruit systems also supports combined B + Ca programs for firmer tissues and longer shelf life, consistent with their complementary roles in cell-wall structure and fruit integrity (Islam et al., 2016).

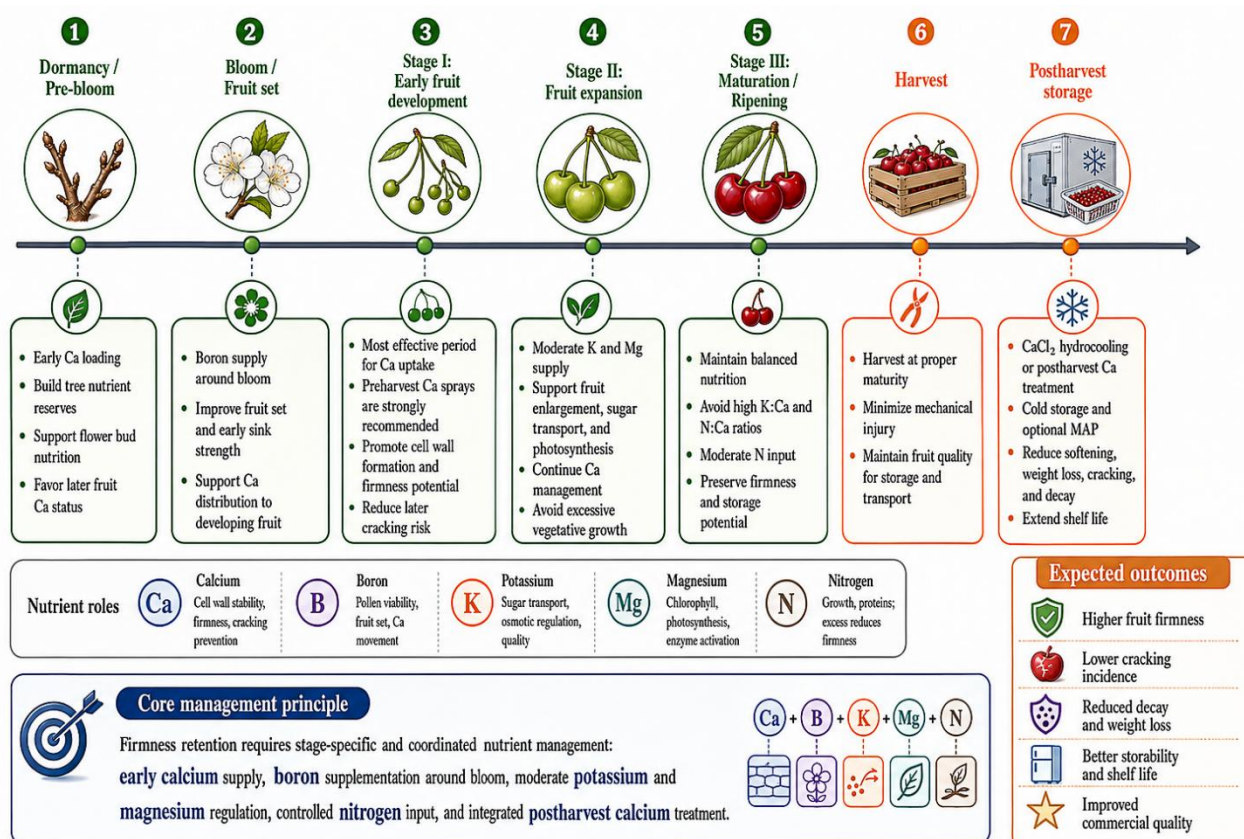


Figure 2 Stage-specific nutrient management strategy for enhancing sweet cherry firmness and shelf life

Image caption: Early calcium supply during dormancy, bloom, and Stage I fruit development is emphasized because calcium import into fruit declines as xylem function weakens. Boron should be supplied around flowering, while potassium and magnesium should be moderately regulated during fruit enlargement and maturation. Postharvest calcium treatment and cold storage technologies can further delay firmness loss

4.2 Fruit expansion and maturation-stage nutrition

During fruit enlargement, nutrient management must support cell expansion and sugar accumulation without allowing calcium dilution, nutrient imbalance, or excessive vegetative growth to weaken firmness (Matteo et al., 2022; Ateş et al., 2022; He et al., 2025). This stage is where the benefits of potassium become clear, but also where antagonism between potassium and calcium becomes a major management concern (Ateş et al., 2022; He et al., 2025).

Potassium is strongly associated with cherry fruit quality and can increase fruit size, weight, soluble solids, and firmness when adequately supplied (Ateş et al., 2022; Santos et al., 2024). In sweet cherry, soil K application before full bloom increased fruit length by 9%, fruit weight by 23%, flesh firmness by 24%, and water-soluble dry matter by 20% (Ateş et al., 2022). However, potassium can also decrease fruit calcium and magnesium concentrations, and increasing the K:Ca ratio can hinder calcium uptake and weaken the mineral balance associated with firm fruit (Ateş et al., 2022; He et al., 2025). This balance matters because fruit calcium concentrations naturally decline during development through reduced import and dilution by growth, so late enlargement strategies should combine potassium support with continued calcium management rather than emphasizing K alone (Matteo et al., 2022; Winkler et al., 2020).

Balanced fertilization is essential because sweet cherry fruit compete with vegetative sinks for both carbohydrates and nutrients during their short development period (Matteo et al., 2022; Santos et al., 2024). Nitrogen supports canopy development and photosynthesis, but excess nitrogen promotes excessive vegetative growth at the expense of fruit formation and maturation and is associated with fruit softening (Varaldo and Giacalone, 2025; Varaldo et

al., 2023). Recent foliar nutrient trials also suggest that nitrogen-containing formulations can accelerate cell expansion and softening, which may compromise cell-wall integrity even when fruit growth is improved (Varaldo et al., 2023). For firmness-oriented orchard management, the target should therefore be moderate vegetative vigor, adequate leaf area, and nutrient ratios that avoid excessive N:Ca and K:Ca imbalance (Matteo et al., 2022; He et al., 2025).

4.3 Foliar and soil application strategies

Both foliar and soil nutrient delivery can contribute to firmness and shelf life, but they serve different purposes: foliar sprays are faster and more target-oriented for short-term correction, whereas soil fertilization and fertigation are better suited to maintaining seasonal nutrient availability and root-zone balance (Bons and Sharma, 2023). The most effective programs integrate both approaches according to phenological stage and nutrient mobility (Santos et al., 2024).

Foliar calcium sprays can improve firmness, reduce cracking, and enhance storage performance, but their effects are often inconsistent because calcium penetration into cherry fruit is erratic and declines with fruit age (Winkler and Knoche, 2019). Timing is therefore critical. In unthinned trees, a Stage I CaCl_2 spray produced higher firmness than sprays at Stages II or III, while early sprays improved fruit textural properties even under high crop load (Matteo et al., 2022). Later sprays can still be useful for cracking reduction, since applications at 39 or 62 days after full bloom reduced cracking in thinned trees (Matteo et al., 2022). Cultivar response remains variable, with calcium improving firmness in Sweetheart and Regina but not Bing in one study, so spray programs should be adjusted by cultivar and local conditions.

Soil fertilization and fertigation remain the foundation for sustaining nutrient supply across the season, particularly for potassium, magnesium, nitrogen, and background calcium and boron nutrition (Arredondo et al., 2024; Santos et al., 2024). Soil K fertilization applied under the canopy before bloom improved several fruit quality traits, showing that root-zone supply can effectively influence later firmness and soluble solids (Ateş et al., 2022). Boron management through the soil is also stage-sensitive: application at full bloom enhances absorption and whole-tree distribution more than application before leaf senescence, while late-season soil B may still help build reserves for the following year (Arredondo et al., 2024). More broadly, root-zone nutrient management should avoid indiscriminate fertilizer use, because excess input can impair mineral balance and create environmental costs, whereas stage-specific nutrient modulation and synchronized fertigation improve both nutrient-use efficiency and fruit quality outcomes (He et al., 2025).

5 Effects of Nutrient Management on Cherry Shelf Life

5.1 Reduction of postharvest softening

Postharvest softening is a primary limit on cherry shelf life, and mineral nutrition can slow this process by preserving wall structure and reducing physiological deterioration. The strongest evidence supports calcium, including both preharvest sprays and postharvest dips, although some newer work suggests calcium source and combination treatments also matter (Belge et al., 2017; Wu et al., 2023).

Calcium delays softening by reducing the activity of enzymes that degrade pectin and other wall polysaccharides during storage (Çelik et al., 2022). In Chinese cherry, preharvest calcium treatments reduced PME, PG, Cx, and β -Gal activities and down-regulated key softening-related genes, indicating direct suppression of cell wall disassembly (Wu et al., 2023). In ‘Celeste’ sweet cherry, calcium treatment increased firmness and was associated with changes in cell wall metabolism, while cold storage itself inhibited Pa β Gal and PaEXP1 transcript accumulation before expression partly recovered during shelf life (Belge et al., 2017). These findings are consistent with the broader interpretation that calcium helps maintain the middle lamella and slows the resolution of pectic structure that normally accompanies ripening and storage (Erbaş and Koyuncu, 2023).

Calcium also prolongs shelf life by maintaining membrane stability and lowering oxidative deterioration during storage. Postharvest calcium application in hydro-cooling water increased fruit tissue calcium by 29%–85% in

‘Sweetheart’ and 39%–188% in ‘Lapins’, while reducing respiration, membrane lipid peroxidation, ascorbic acid degradation, titratable acidity loss, decay, and pitting (Wang et al., 2014). In Chinese cherry, exogenous calcium decreased malondialdehyde content and relative electrical conductivity while increasing antioxidant enzyme activities, which supports a membrane-protective role beyond simple wall strengthening (Wu et al., 2023). Combined pre- and postharvest calcium gluconate similarly suppressed respiration and delayed losses of firmness, acidity, sensory quality, and decay during cold storage, although responses varied with calcium source and treatment sequence (Erbaş and Koyuncu, 2023).

5.2 Improvement of resistance to cracking and decay

Nutrient management also affects shelf life indirectly by reducing skin failure before or after harvest and by limiting subsequent microbial invasion. This relationship is important because cracked fruit are much more vulnerable to fungal infection and commercial rejection (Çolak et al., 2025).

Calcium consistently reduces cracking in many cherry studies, although the magnitude varies. Preharvest foliar calcium treatments reduced cracking by 38%–66% in ‘0900 Ziraat’, with calcium chloride and calcium hydroxide among the most effective compounds, and calcium chloride also increased firmness by about 12% relative to other compounds (Eroğul, 2014). More recent orchard trials found that calcium- and potassium-based foliar treatments reduced cracking and improved firmness and weight retention during storage, while dormant-bud calcium application also lowered on-tree cracking and improved harvest quality traits (Michailidis et al., 2021; Varaldo and Giacalone, 2025). Boron contributes mainly through its interaction with calcium transport and wall structure. Under boron-deficient soil, calcium allocation shifted toward roots and pits, while calcium in the edible flesh and peel was higher under boron-adequate conditions, indicating that boron deficiency weakens the calcium status most relevant to cracking resistance (Bonomelli et al., 2025).

Reduced decay after calcium treatment appears to reflect both stronger tissues and slower physiological breakdown. Calcium-treated ‘Celeste’ fruit had lower decay incidence than controls (Belge et al., 2017). Hydro-cooling with calcium chloride decreased decay in both ‘Sweetheart’ and ‘Lapins’ cherries, alongside lower membrane lipid peroxidation and respiration (Wang et al., 2014). A mechanistic explanation is that calcium promotes pectate formation, strengthens intercellular adhesion, and suppresses wall-degrading enzymes, which makes pathogen penetration more difficult (Çolak et al., 2025). Nutrient balance also matters because excess nitrogen appears to favor softening, and calcium responses are often inconsistent when uptake into fruit is limited or mineral ratios are unfavorable (Winkler and Knoche, 2019).

5.3 Interaction with storage conditions

Nutrient effects on shelf life are strongest when considered together with storage environment, especially low temperature and modified atmosphere packaging. The evidence supports synergy between calcium status and storage technology, but also shows that storage conditions can either reveal or mask nutrient benefits (Matteo et al., 2022; Liu et al., 2025; Cui et al., 2025).

Cold storage preserves cherries, but fruit nutrient status strongly influences how well quality is maintained over time. Early crop load reduction improved storage condition after 45 days at 0 °C, and early foliar CaCl₂ sprays improved firmness under high crop load, indicating that preharvest calcium management can improve cold storage performance before fruit enter storage (Matteo et al., 2022). Calcium-treated fruit generally lose less weight and maintain greater firmness during refrigerated storage, as shown in ‘Celeste’, ‘Regina’, and ‘Sweetheart’ studies (Varaldo and Giacalone, 2025). Combined pre- and postharvest calcium gluconate was especially effective during three weeks of cold storage, giving the best suppression of respiration and the slowest losses of firmness and sensory quality (Erbaş and Koyuncu, 2023).

Modified atmosphere packaging improves cherry storage by lowering respiration and water loss, and nutrient treatments can enhance these benefits. MAP significantly retarded weight loss and, when combined with a preharvest treatment, helped maintain firmness and reduce decay during cold storage and shelf life in ‘0900 Ziraat’

(Aglar et al., 2017). Postharvest CaCl_2 plus MAP reduced respiration and preserved quality traits and bioactive compounds better than untreated controls, with the lowest decay and weight loss generally occurring in the combined treatment during storage (Çolak et al., 2025). Optimized MAP also maintained firmness, acidity, vitamin C, and lower browning and decay over long cold storage, but its success depended on film permeability and gas composition, so nutrient benefits are contingent on a well-matched storage atmosphere rather than MAP alone (Cui et al., 2025).

6 Integrated Orchard Practices Supporting Nutrient Management

6.1 Irrigation and nutrient uptake coordination

Water management strongly conditions nutrient uptake because calcium transport depends on xylem flow, while potassium acquisition and distribution respond to root activity and soil solution dynamics (Figure 3). In sweet cherry, higher irrigation volumes were associated with lower cracking at harvest and were hypothesized to favor calcium uptake and incorporation into fruit cells, even though final fruit Ca concentration differences were not always significant (Measham et al., 2013). This inconsistency matches broader review evidence showing that calcium effects on cherry quality are often variable because Ca movement into fruit is physiologically constrained and sometimes erratic (Winkler and Knoche, 2019).

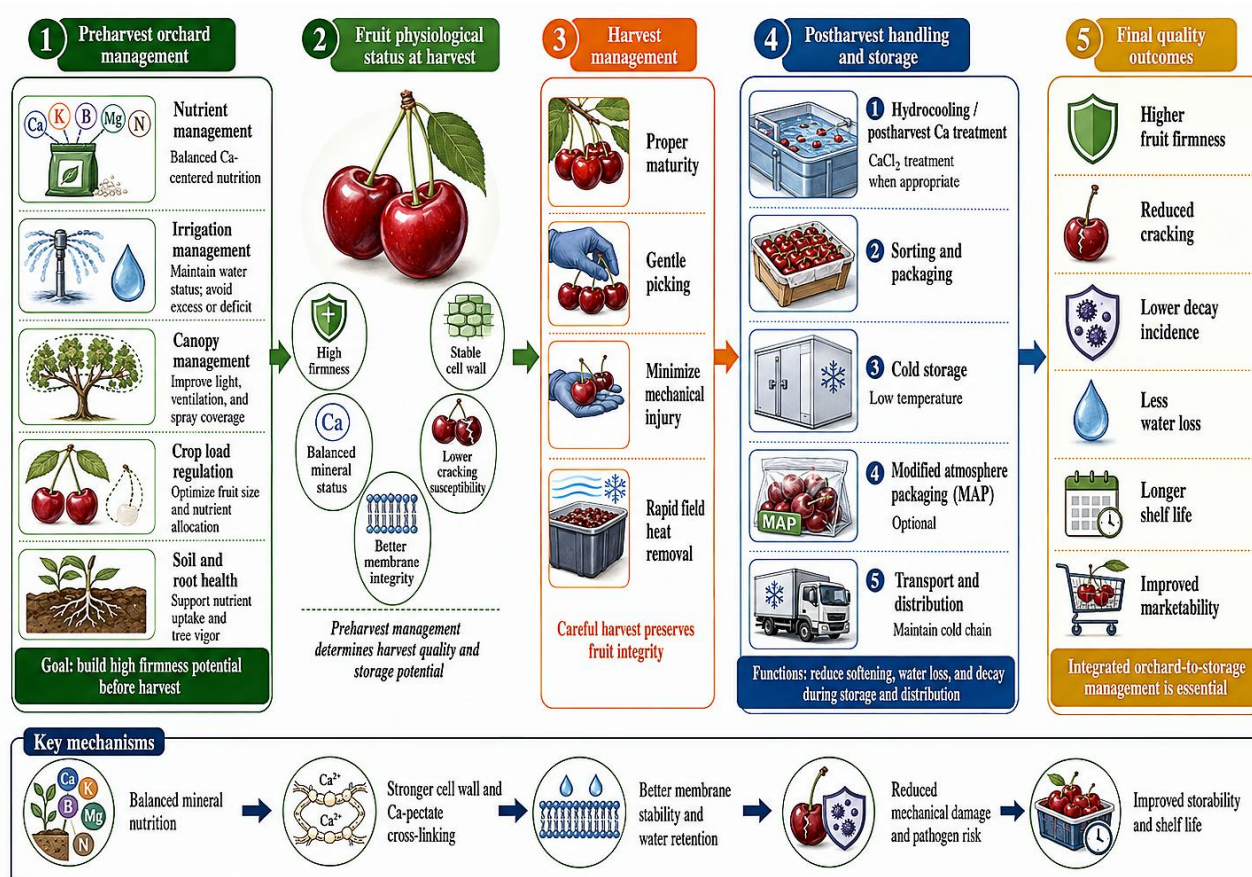


Figure 3 Integrated preharvest and postharvest management system for extending sweet cherry shelf life

Orchard nutrient management should be coordinated with irrigation, canopy structure, crop load regulation, soil health, postharvest calcium treatment, cold storage, and modified atmosphere packaging. This integrated system helps reduce softening, cracking, decay, water loss, and quality deterioration during storage and distribution

Soil moisture affects calcium most directly because Ca is xylem-mobile and fruit import declines as development proceeds, so sustained water supply early in fruit growth helps maintain transport to the fruit (Winkler and Knoche, 2019; Matteo et al., 2022). Potassium responds differently: K fertilization increased fruit size, weight, firmness, and soluble solids, but also reduced fruit Ca and Mg concentrations, showing that uptake benefits can be

offset by antagonism if water and fertilizer management drive excessive K relative to Ca (Ateş et al., 2022). Environmental conditions also modify these responses, since rainfall and temperature significantly influenced cherry quality parameters in a three-year fertilization study, emphasizing that nutrient outcomes cannot be separated from orchard water status (Santos et al., 2024).

Fertigation improves nutrient-use efficiency when timing is synchronized with developmental demand rather than applied as a large undifferentiated seasonal dose. Sweet cherry management benefits from understanding nutrient availability during blossom, fruit growth, harvest, and postharvest periods, because synchronized fertilization improves application efficiency and fruit quality (Santos et al., 2024). Although the strongest direct fertigation evidence in the supplied set comes from broader fruit-crop literature, integrated soil fertility management in perennial fruit systems consistently shows that combining inorganic fertilizers with organic inputs and microbial inoculants improves agronomic response and soil health more effectively than relying on a single nutrient source (Srivastava et al., 2021). In practice, efficient fertigation for cherry should therefore emphasize moderate, stage-specific nutrient supply and avoid indiscriminate chemical fertilization, which has been identified more generally as a cause of poor nutrient balance and lower system efficiency (Srivastava et al., 2021; Varaldo et al., 2023).

6.2 Canopy and crop load management

Canopy architecture and crop load regulate how effectively nutrient supply is converted into fruit quality because they determine light interception, carbon assimilation, and competition among fruit and vegetative sinks. Low-light stress in sweet cherry reduces leaf light capture, damages photosynthetic performance, restricts carbon assimilation, and reduces nutrient accumulation in fruit (Tang et al., 2023). At the same time, fruit yield and quality are positively related to leaf area per fruit, and heavy crop load is associated with smaller, poorer-quality cherries (Matteo et al., 2022).

A favorable canopy light environment supports fruit nutrient accumulation indirectly by sustaining photosynthesis and carbohydrate export to fruit. In sweet cherry, shading reduced fruit weight, sugar content, and vitamin C, while increasing acidity, consistent with lower assimilate availability and poorer maturation under canopy closure (Tang et al., 2023). Evidence from other fruit trees points in the same direction: fruit in better-lit canopy positions accumulated more sugars, dry matter, and secondary metabolites in apple, and exposed high-light fruit showed more favorable metabolite profiles in peach (Anthony et al., 2021; Kviklys et al., 2022). Training systems therefore matter nutritionally as well as structurally, because adequate spacing and planar canopy organization improve light interception and support higher dry matter and soluble solids under commercial cherry production (Stone et al., 2022).

Crop load regulation improves fruit uniformity by reducing competition for carbohydrates and minerals among fruit. Early crop load reduction increased fruit size and weight, and thinned trees showed less pedicel detachment, browning, and decay after 45 days of storage at 0 °C (Matteo et al., 2022). Under high crop load, an early Stage I CaCl₂ spray produced firmer fruit than later sprays, indicating that crop load also alters the effectiveness of nutrient interventions rather than only baseline fruit quality. More broadly, the negative correlations between crop load and fruit dry matter or soluble solids in sweet cherry training-system trials show that uniform quality requires balancing crop number with canopy source capacity, not simply increasing fertilizer supply (Stone et al., 2022).

6.3 Soil health and organic amendments

Soil health practices support nutrient management by improving organic matter, root activity, and the biological processes that regulate nutrient cycling. Reviews across fruit systems show that integrated use of organic fertilizers, composts, and microbial inoculants has become central to sustainable soil fertility management because it improves soil health while supporting quality production (Srivastava et al., 2021; Singh et al., 2024). These practices are especially relevant in perennial orchards, where long-term root-zone function shapes yearly nutrient uptake more than short-term fertilizer additions alone.

Organic matter improvement promotes root activity by enhancing moisture retention, nutrient availability, and the physical environment of the rhizosphere. Soil organic matter is a major driver of soil quality because it affects pH, moisture retention, and nutrient concentrations (Xie et al., 2024). More generally, organic amendments provide a slow-release bank of macro- and micronutrients while improving physical and biological soil properties (Singh et al., 2024). In orchard systems, amendments and biologically active carriers increased root length density and shoot growth in apple, indicating that improved soil conditions can translate into stronger root systems and higher nutrient capture capacity (Ding et al., 2024).

Microbial amendments improve nutrient availability mainly by reshaping rhizosphere communities and strengthening nutrient cycling. Soil amendments increased fungal diversity, increased microbial network complexity, and enhanced bacterial–fungal synergy linked to nutrient cycling functions (Ding et al., 2024). In pear, bio-organic fertilizers increased yield by up to 20%, and adding beneficial bacteria tripled the yield increase achieved by organic fertilizer alone, largely through altered soil chemistry and a more plant-beneficial microbiome (Wang et al., 2022). Integrated fruit-tree intercropping systems likewise increased organic matter, available phosphorus, and available potassium while increasing beneficial microbial groups related to disease prevention and nutrient cycling, although they also carried risks such as soil acidification that require corrective management (Xie et al., 2024).

7 Challenges and Future Development of Cherry Nutrient Management

7.1 Current problems in nutrient management

A central problem is that nutrients are not distributed uniformly among fruits, leaves, peduncles, prunings, and perennial organs. In sweet cherry orchards, N was more evenly distributed across fruits, peduncles, and prunings, whereas K was concentrated in fruits and peduncles and Ca and Mg were retained mainly in fallen leaves, showing that fruit demand does not mirror whole-tree nutrient status (Karampatzakis et al., 2025). Under high yields, K was redistributed from leaves to fruits, further indicating that internal remobilization can intensify organ-to-organ imbalance. Uneven distribution also occurs within the fruit itself: calcium concentration was two- to three-fold higher at the stem end than at the styler end, and fruit-to-fruit variation in calcium mass was wide even within cultivars (Winkler et al., 2020). Source–sink imbalance compounds this heterogeneity because sweet cherry fruit develop rapidly, compete strongly with vegetative sinks, and depend on adequate leaf area per fruit for uniform quality formation (Matteo et al., 2022).

A second persistent problem is the tendency toward excessive or poorly balanced fertilization. Precision-nutrition reviews note that conventional nutrient management often leads to over-fertilization, uneven nutrient supply, environmental pollution, and economic inefficiency (Singh et al., 2024). Cherry-specific studies likewise emphasize the lack of site-specific fertilization guidelines and the need to account for nutrient removal and recycling rather than replacing nutrients generically (Karampatzakis et al., 2025). Antagonistic interactions make this problem more serious: high K levels can reduce Ca and Mg status, and high nitrogen can depress leaf P and K while also lowering leaf Ca and Mg at excessive rates (Rutkowski and Łysiak, 2023). In sweet cherry fruit, increasing K or N can therefore improve some growth traits while simultaneously worsening the mineral balance associated with firmness and storage potential (Santos et al., 2024).

7.2 Technical limitations in improving firmness and shelf life

The main technical limitation is the difficulty of delivering calcium into cherry fruit at the right place and time. Calcium influx is positively related to transpiration and declines as xylem functionality is progressively lost during fruit development, making late-season correction inherently difficult (Winkler et al., 2020). Natural fruit calcium concentrations also decline during development because import slows while continued growth dilutes accumulated calcium (Matteo et al., 2022). Reviews conclude that preharvest sprays and postharvest dips sometimes increase fruit calcium and improve firmness, cracking, or rot resistance, but at other times they are ineffective because calcium movement through the cuticle is erratic and the uptake pathways remain poorly understood (Winkler and Knoche, 2019). Even when calcium enters tissues, responses are spatially selective:

dormant applications reached flower buds and phloem but not vegetative buds, and postharvest hydrocooling increased tissue Ca while reducing pectin solubilization, splitting, decay, and firmness loss (Wang and Long, 2015; Michailidis et al., 2021).

Another limitation is strong variation among cultivars, seasons, and regions. Calcium effects are not always consistent across studies, and cultivar-specific responses are common (Winkler et al., 2020). In one cherry study, calcium improved firmness in Sweetheart and Regina but not in Bing, and fruit Ca concentration responded significantly only in Regina. Seasonal and regional conditions also reshape nutrient outcomes: year effects strongly altered fruit size and quality in Mg/K fertilization trials, and temperature and rainfall were identified as major influences on cherry quality responses (Santos et al., 2024). Even orchards under similar management can differ because of soil texture, pH, age, and rootstock effects, which complicates the transfer of fertilizer recommendations across regions (Karampatzakis et al., 2025).

7.3 Future development trends

Future development will likely center on precision nutrient management based on fruit demand rather than fixed fertilizer schedules. Precision approaches aim to supply the right nutrient amount at the right time and place using real-time information on soil conditions, plant health, and nutrient status (Singh et al., 2024). In cherry, this direction is supported by yield-based nutrient-removal models, where fresh fruit yield showed strong relationships with uptake of N, P, K, Mg, B, and Cu, enabling prediction of orchard nutrient losses (Karampatzakis et al., 2025). Because large fractions of N, P, K, and Mg remain in leaves and prunings, future programs should integrate nutrient recycling with external inputs rather than treating annual fertilization as one-way replacement. Sustainable organic options may also contribute, since compost tea plus compost improved tree water status, photosynthetic performance, yield, and fruit quality in an organic cherry orchard (Gaeta et al., 2025).

A second major trend is the integration of sensors, prediction models, and quality analytics to connect orchard nutrition with firmness and shelf-life outcomes. Reviews of precision nutrient management in fruit crops emphasize remote sensing, variable-rate technology, fertigation, and data-driven decision tools, but also note that validation for specific fruit crops remains limited (Singh et al., 2024). New sensing studies in other fruit systems show that hyperspectral imaging and machine learning can non-destructively predict soluble solids, nutrients, vitamin C, and protein across varieties and seasons, while soil-sensor networks can estimate harvest quality traits from field measurements (Elashmawy and Uysal, 2023; Zhai et al., 2025). Broader Agriculture 4.0 reviews similarly argue that multimodal sensors and AI can improve real-time fruit quality evaluation, although interpreting interacting effects of nutrient imbalance, stress, and disease remains technically complex (Colaco and Kamat, 2025). For cherry, the next step is to combine these tools with nutrient-uptake models and postharvest indicators so that fertilization decisions can be evaluated not only by yield, but by predicted firmness retention, cracking risk, and storage performance.

8 Conclusions and Perspectives

Nutrient regulation is an important approach for improving cherry fruit firmness and storability. Among the relevant nutrients, calcium is most directly associated with fruit firmness and storage performance. Calcium strengthens cell wall structure, maintains membrane system stability, and is closely related to reduced fruit cracking and decay, as well as higher firmness at harvest and during storage. However, the regulatory effect of calcium is strongly constrained by fruit developmental physiology. As fruit enlarge and xylem function declines, calcium influx into the fruit gradually weakens, and fruit calcium concentration is also likely to decrease because of dilution effects. Potassium plays a positive role in promoting fruit enlargement, sugar accumulation, and ripening, and some studies have also shown that it helps maintain firmness. Nevertheless, excessive potassium supply may increase the K:Ca ratio, disrupt calcium and magnesium balance, and consequently weaken fruit storage performance. Magnesium mainly acts indirectly by supporting photosynthesis, carbon assimilation, and quality formation, and its contribution to firmness improvement usually depends on an appropriate

calcium–magnesium balance. Boron participates in quality regulation mainly by affecting cell wall structure, nutrient transport, fruit set, and early fruit development, and may promote calcium allocation to edible fruit tissues.

Existing studies indicate that supplementation with a single nutrient is unlikely to consistently improve cherry firmness and storage quality, whereas coordinated regulation of multiple nutrients has greater practical value. Early calcium supplementation, especially at the dormant-bud stage or during Stage I of fruit development, is more favorable for calcium entry into flower buds, phloem, and young fruit tissues, where it can participate in cell wall formation. Although late calcium treatment may have limited effects on firmness improvement, it may still reduce fruit cracking. Combined foliar programs based on calcium and potassium have shown certain advantages in maintaining firmness during storage and reducing weight loss and cracking. Postharvest hydrocooling with 0.2%–0.5% CaCl_2 can also help maintain fruit firmness after cold storage and reduce cracking, decay, acidity loss, and skin discoloration. Therefore, cherry nutrient management should shift from single-element fertilization toward integrated regulation based on developmental stage, nutrient ratios, and postharvest requirements.

In production practice, a stage-specific and balanced nutrient management model should be established. Calcium supply should be advanced, with emphasis on the dormant period, flowering stage, and early fruit development. Boron supply should be ensured around flowering to promote fruit set and early fruit development. Potassium and magnesium can be moderately adjusted from fruit enlargement to ripening to improve fruit size, sugar–acid accumulation, and color quality, but excessive application should be avoided to prevent K:Ca imbalance and fruit softening. Nitrogen management should also remain moderate, because excessive nitrogen application may not only affect leaf phosphorus, potassium, calcium, and magnesium contents, but also weaken fruit quality stability. Meanwhile, preharvest thinning, crop-load regulation, and postharvest calcium treatment should be applied in coordination to establish an integrated technical system from orchard management to postharvest preservation.

Future research should further deepen both mechanistic analysis and precision management. On the one hand, it is necessary to clarify the pathways of calcium uptake, cuticular penetration, tissue distribution, and cellular localization in cherry fruit, and to reveal the relationships between elements such as calcium, potassium, magnesium, and boron and cell wall metabolism, membrane stability, ripening regulation, and the expression of softening-related genes. On the other hand, cultivar and site-specific differences should be emphasized, and nutrient management programs suitable for different cultivars, rootstocks, tree ages, soil conditions, and yield levels should be developed. With advances in hyperspectral imaging, soil sensors, nutrient uptake models, and artificial intelligence, cherry nutrient management is expected to move toward a cultivar-specific, sensor-assisted, and recycling-oriented precision model.

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The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Reference

- Anthony B.M., Chaparro J.M., Sterle D.G., Prenni J.E., and Minas I.S., 2021, Metabolic signatures of the true physiological impact of canopy light environment on peach fruit quality, *Environmental and Experimental Botany*, 191: 104630.
<https://doi.org/10.1016/j.envexpbot.2021.104630>
- Arredondo G., Bonomelli C., Nario A., Rojas-Silva X., and Gaete P., 2024, Sweet cherry response in absorption and mobility of 10B applied to soil and flowers under two soil boron conditions, *Journal of Plant Nutrition and Soil Science*.
<https://doi.org/10.1002/jpln.202400098>
- Ateş Ö., Alveroglu V., Turhan E., Yalçın G., Taşpınar K., and Kizilaslan F., 2022, Effects of potassium fertilization on sweet cherry fruit (*Prunus avium* L.) quality and mineral content, *Communications in Soil Science and Plant Analysis*, 53(14): 1777-1782.
<https://doi.org/10.1080/00103624.2022.2063322>

- Aglar E., Ozturk B., Guler S.K., Karakaya O., Uzun S., and Saracoglu O., 2017, Effect of modified atmosphere packaging and 'Parka' treatments on fruit quality characteristics of sweet cherry fruits (*Prunus avium* L. '0900 Ziraat') during cold storage and shelf life, *Scientia Horticulturae*, 222: 162-168.
<https://doi.org/10.1016/j.scienta.2017.05.024>
- Beinsan C., Velicevici G., Sumalan R., Scedei D., and Borza M., 2025, Studies on quality characteristics after fruit storage in some cherry varieties, *Journal of Horticulture, Forestry and Biotechnology*, 29(2): 369-377.
<https://doi.org/10.59463/dcv8e427>
- Belge B., Goulao L.F., Comabella E., Graell J., and Lara I., 2017, Refrigerated storage and calcium dips of ripe 'Celeste' sweet cherry fruit: Combined effects on cell wall metabolism, *Scientia Horticulturae*, 219: 182-190.
<https://doi.org/10.1016/j.scienta.2017.02.039>
- Blanco V., Zoffoli J.P., and Ayala M., 2021, Influence of high tunnel microclimate on fruit quality and calcium concentration in 'Santina' sweet cherries in a Mediterranean climate, *Agronomy*, 11(6): 1186.
<https://doi.org/10.3390/agronomy11061186>
- Bonomelli C., Arredondo G., Nario A., Artacho P., and Contreras C., 2025, Calcium allocation to the tree canopy and the edible part of sweet cherry fruit is hindered by boron soil deficiency, *Agronomy*, 15(3): 691.
<https://doi.org/10.3390/agronomy15030691>
- Bons H.K., and Sharma A., 2023, Impact of foliar sprays of potassium, calcium, and boron on fruit setting behavior, yield, and quality attributes in fruit crops: A review, *Journal of Plant Nutrition*, 46(13): 3232-3246.
<https://doi.org/10.1080/01904167.2023.2192242>
- Chockchaisawasdee S., Golding J.B., Vuong Q.V., Papoutsis K., and Stathopoulos C.E., 2016, Sweet cherry: Composition, postharvest preservation, processing and trends for its future use, *Trends in Food Science and Technology*, 55: 72-83.
<https://doi.org/10.1016/j.tifs.2016.07.002>
- Colaco L., and Kamat P., 2025, Artificial intelligence advances for cashew fruit maturity and quality detection: A systematic review on models, sensors, and farming applications, *Journal of Big Data*, 12(1): 250.
<https://doi.org/10.1186/s40537-025-01296-2>
- Correia S., Schouten R., Silva A.P., and Gonçalves B., 2017, Factors affecting quality and health promoting compounds during growth and postharvest life of sweet cherry (*Prunus avium* L.), *Frontiers in Plant Science*, 8: 2166.
<https://doi.org/10.3389/fpls.2017.02166>
- Cui J., Jia X., Wang W., Fan L., Zhao W., He L., and Xu H., 2025, Effects of modified atmosphere packaging on postharvest physiology and quality of 'Meizao' sweet cherry (*Prunus avium* L.), *Agronomy*, 15(8): 1774.
<https://doi.org/10.3390/agronomy15081774>
- Ding Y., Gao X., Shu D., Siddique K., Song X., Wu P., Li C., and Zhao X., 2024, Enhancing soil health and nutrient cycling through soil amendments: Improving the synergy of bacteria and fungi, *The Science of the Total Environment*: 171332.
<https://doi.org/10.1016/j.scitotenv.2024.171332>
- Elashmawy R., and Uysal I., 2023, Precision agriculture using soil sensor driven machine learning for smart strawberry production, *Sensors*, 23(4): 2247.
<https://doi.org/10.3390/s23042247>
- Erbaş D., and Koyuncu M.A., 2021, Effects of calcium treatment on physical and biochemical changes of cold-stored sweet cherry fruit, *Horticultural Studies*, 38(1): 15-22.
<https://doi.org/10.16882/hortis.841633>
- Erbaş D., and Koyuncu M.A., 2023, The effect of pre- and postharvest calcium gluconate treatments on physicochemical characteristics and bioactive compounds of sweet cherry during cold storage, *Food Science and Technology International*, 29(4): 299-309.
<https://doi.org/10.1177/10820132221077515>
- Eroglu D., 2014, Effect of preharvest calcium treatments on sweet cherry fruit quality, *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 42: 150-153.
<https://doi.org/10.15835/nbha4219369>
- Gaeta L., Tarricone L., Persiani A., Fiore A., Montemurro F., De Benedetto D., Vitti C., Campi P., and Diacono M., 2025, Sustainable fertilization of organic sweet cherry to improve physiology, quality, yield, and soil properties, *Agronomy*, 15(1): 135.
<https://doi.org/10.3390/agronomy15010135>
- Guo X., Li Q., Luo T., Han D., Zhu D., and Wu Z., 2023, Postharvest calcium chloride treatment strengthens cell wall structure to maintain litchi fruit quality, *Foods*, 12(13): 2478.
<https://doi.org/10.3390/foods12132478>
- He Y., Su K., Wang L., Zhou J., Sun S., Wang J.E., and Xing G., 2025, Modulation of potassium-to-calcium ratio in nutrient solution improves quality attributes and mineral composition of *Solanum lycopersicum* var. *cerasiforme*, *Agronomy*, 15(6): 1380.
<https://doi.org/10.3390/agronomy15061380>
- Hocking B., Tyerman S.D., Burton R.A., and Gilliam M., 2016, Fruit calcium: transport and physiology, *Frontiers in Plant Science*, 7: 569.
<https://doi.org/10.3389/fpls.2016.00569>
- Islam M.Z., Mele M.A., Baek J.P., and Kang H.M., 2016, Cherry tomato qualities affected by foliar spraying with boron and calcium, *Horticulture, Environment, and Biotechnology*, 57(1): 46-52.
<https://doi.org/10.1007/s13580-016-0097-6>

- Ivanova I., Serdiuk M., Tymoshchuk T., Bulygin S., and Moisiienko V., 2023, Assessment of sweet cherry fruit quality according to the requirements of the modern market, *Plant and Soil Science*, 14(2).
<https://doi.org/10.31548/plant2.2023.21>
- Jaime-Guerrero M., Álvarez-Herrera J.G., and Fischer G., 2024, Effect of calcium on fruit quality: A review, *Agronomía Colombiana*, 42(1): 1-14.
<https://doi.org/10.15446/agron.colomb.v42n1.112026>
- Karampatzakis I., Biliás F., Polychroniadou C., Tanou G., Kekelis P., Theofilidou A., Giannopoulos G., Pavlatou-Ve A., and Aschonitis V., 2025, Assessing nutrient losses and recycling in sweet cherry orchards: A yield-based approach, *Agriculture*, 15(12): 1312.
<https://doi.org/10.3390/agriculture15121312>
- Kviklys D., Viškelis J., Liaudanskas M., Janulis V., Laužikė K., Samuolienė G., Uselis N., and Lanauskas J., 2022, Apple fruit growth and quality depend on the position in tree canopy, *Plants*, 11(2): 196.
<https://doi.org/10.3390/plants11020196>
- Liu L., Lin H., Zhou X., Zhang Z., Zhang Y., Deng S., Peng S., Gong S., Guo S., and Fan W., 2025, Application of modified atmosphere preservation technology in cherry storage: A review, *Agriculture*, 15(5): 462.
<https://doi.org/10.3390/agriculture15050462>
- Long Y., and Peng J., 2023, Interaction between boron and other elements in plants, *Genes*, 14(1): 130.
<https://doi.org/10.3390/genes14010130>
- Matteo M., Zoffoli J.P., and Ayala M., 2022, Calcium sprays and crop load reduction increase fruit quality and postharvest storage in sweet cherry (*Prunus avium* L.), *Agronomy*, 12(4): 829.
<https://doi.org/10.3390/agronomy12040829>
- Measham P.F., Gracie A.J., Wilson S.J., and Bound S.A., 2013, Nutrition and irrigation: towards a practical solution for cherry cracking, *Acta Horticulturae*, 984: 409-414.
<https://doi.org/10.17660/actahortic.2013.984.50>
- Michailidis M., Bazakos C., Kollaros M., Adamakis I.D.S., Ganopoulos I., Molassiotis A., and Tanou G., 2023, Boron stimulates fruit formation and reprograms developmental metabolism in sweet cherry, *Physiologia Plantarum*, 175(3): e13946.
<https://doi.org/10.1111/ppl.13946>
- Michailidis M., Polychroniadou C., Kosmidou M.A., Petraki-Katsoulaki D., Karagiannis E., Molassiotis A., and Tanou G., 2021, An early calcium loading during cherry tree dormancy improves fruit quality features at harvest, *Horticulturae*, 7(6): 135.
<https://doi.org/10.3390/horticulturae7060135>
- Michailidis M., Titeli V.S., Karagiannis E., Feidaki K., Ganopoulos I., Tanou G., Argiriou A., and Molassiotis A., 2022, Tissue-specific transcriptional analysis outlines calcium-induced core metabolic changes in sweet cherry fruit, *Plant Physiology and Biochemistry*, 189: 139-152.
<https://doi.org/10.1016/j.plaphy.2022.08.022>
- Pakkish Z., and Mohammadrezakhani S., 2022, The effect of preharvest application of arginine on the postharvest quality of sweet cherry fruits during storage, *International Journal of Fruit Science*, 22(1): 837-851.
<https://doi.org/10.1080/15538362.2022.2134272>
- Parveze M.U., Mir M.M., Rehman M., Iqbal U., Khan S., Khan I., Qayoom S., Mushtaq I., Shah H.K., Gaafar A.-R.Z., and Kaushik P., 2024, Regulation of crop load and quality in sweet cherry cv. 'Sweet Heart' using blossom thinning, *Folia Horticulturae*, 36(2): 311-321.
<https://doi.org/10.2478/fhort-2024-0020>
- Posé S., Paniagua C., Matas A.J., Gunning A.P., Morris V.J., Quesada M.A., and Mercado J.A., 2019, A nanostructural view of the cell wall disassembly process during fruit ripening and postharvest storage by atomic force microscopy, *Trends in Food Science and Technology*, 87: 47-58.
<https://doi.org/10.1016/j.tifs.2018.02.011>
- Quiroz M.P., Blanco V., Zoffoli J.P., and Ayala M., 2023, Study of mineral composition and quality of fruit using vascular restrictions in branches of sweet cherry, *Plants*, 12(10): 1922.
<https://doi.org/10.3390/plants12101922>
- Rutkowski K., and Łysiak G.P., 2023, Effect of nitrogen fertilization on tree growth and nutrient content in soil and cherry leaves (*Prunus cerasus* L.), *Agriculture*, 13(3): 578.
<https://doi.org/10.3390/agriculture13030578>
- Sandilya A., Prasad V.M., Bahadur V., Singh D., and Singh Y.K., 2023, Response of different level of zinc and boron on growth, flowering, yield and quality of cherry tomato (*Solanum lycopersicum* var. *cerasiforme*) cv. 'Pusa Cherry-1', *International Journal of Environment and Climate Change*, 13(10): 1889-1897.
<https://doi.org/10.9734/ijec/2023/v13i102845>
- Santos M., Pereira S., Ferreira H., Sousa J., Vilela A., Ribeiro C., Raimundo F., Egea-Cortines M., Matos M., and Gonçalves B., 2024, Optimizing sweet cherry attributes through magnesium and potassium fertilization, *Horticulturae*, 10(8): 881.
<https://doi.org/10.3390/horticulturae10080881>
- Singh A.K., Sajwan A., Kamboj A.D., Joshi G., Gautam R., Kumar M., Mani G., Lal S., and Kaur J., 2024, Advances in precision nutrient management of fruit crops, *Journal of Plant Nutrition*, 47(19): 3251-3271.
<https://doi.org/10.1080/01904167.2024.2377411>

- Srivastava A.K., Wu Q.S., Mousavi S.M., and Hota D., 2021, Integrated soil fertility management in fruit crops: An overview, *International Journal of Fruit Science*, 21(1): 413-439.
<https://doi.org/10.1080/15538362.2021.1895034>
- Stone C.H., Close D.C., Bound S.A., and Hunt I., 2022, Training systems for sweet cherry: Light relations, fruit yield and quality, *Agronomy*, 12(3): 643.
<https://doi.org/10.3390/agronomy12030643>
- Su G., Lin Y., Wang C., Lu J., Liu Z., He Z., Shu X., Chen W., Wu R., Li B., Zhu C., Rose J.K.C., Grierson D., Giovannoni J., Shi Y., and Chen K., 2023, Expansin SIExp1 and endoglucanase SICel2 synergistically promote fruit softening and cell wall disassembly in tomato, *The Plant Cell*, 36(3): 709-726.
<https://doi.org/10.1093/plcell/koad291>
- Tang W., Chen C., Zhang Y., Chu Y.-R., Yang W., Cui Y., Kou G., Chen H., Song H.-Y., and Gong R., 2023, Effect of low-light stress on sugar and acid accumulation during fruit development and ripening of sweet cherry, *Horticulturae*, 9(6): 654.
<https://doi.org/10.3390/horticulturae9060654>
- Thakur S., Sinha A., and Ghosh Bag A., 2023, Boron-a critical element for fruit nutrition, *Communications in Soil Science and Plant Analysis*, 54(21): 2899-2914.
<https://doi.org/10.1080/00103624.2023.2252878>
- Usmani L., Shakil A., Khan I., Alvi T., Singh S., and Das D., 2025, Brassinosteroids in micronutrient homeostasis: Mechanisms and implications for plant nutrition and stress resilience, *Plants*, 14(4): 598.
<https://doi.org/10.3390/plants14040598>
- Varaldo A., and Giacalone G., 2025, Enhancing cracking resistance and post-harvest quality of sweet cherries (*Prunus avium* L.) through calcium and potassium-based foliar treatments, *Horticulturae*, 11(1): 30.
<https://doi.org/10.3390/horticulturae11010030>
- Varaldo A., Alchera F., Brigante L., and Giacalone G., 2023, Foliar applications of calcium and potassium increase cracking resistance and enhance fruit quality in sweet cherries, *Italus Hortus*, 30(3): 25-36.
<https://doi.org/10.26353/j.italhort/2023.3.2536>
- Varaldo A., Dacomo A., Donno D., and Giacalone G., 2026, Combined effects of prohexadione-calcium and growing environment on sweet cherry fruit quality and postharvest performance, *Journal of the Science of Food and Agriculture*, 106(8): 4901-4912.
<https://doi.org/10.1002/jsfa.70574>
- Vera-Maldonado P., Aquea F., Reyes-Díaz M., Cárcamo-Fincheira P., Soto-Cerda B., Nunes-Nesi A., and Inostroza-Blancheteau C., 2024, Role of boron and its interaction with other elements in plants, *Frontiers in Plant Science*, 15: 1332459.
<https://doi.org/10.3389/fpls.2024.1332459>
- Wang X., Zhang D., Liu T., Yan Z., Ji X., Li Y., Wu Y., Cheng H., Wang Y., Cui J., Wu Y., and Chen L., 2025, Advances in cell wall dynamics and gene expression in postharvest fruit softening, *Plants*, 14(18): 2831.
<https://doi.org/10.3390/plants14182831>
- Wang Y., and Long L.E., 2015, Physiological and biochemical changes relating to postharvest splitting of sweet cherries affected by calcium application in hydrocooling water, *Food Chemistry*, 181: 241-247.
<https://doi.org/10.1016/j.foodchem.2015.02.100>
- Wang Y., L. Y., Tian T., Zhang J., Wang H., Liu Z.-S., Chen Q., He W., Lin Y., Zhang Y., Li M., Yang S.-F., Zhang Y., Luo Y., Tang H., and Wang X., 2023, Comparative physiological and transcriptomic analyses provide insights into fruit softening in Chinese cherry [*Cerasus pseudocerasus* (Lindl.) G. Don], *Frontiers in Plant Science*, 14: 1190061.
<https://doi.org/10.3389/fpls.2023.1190061>
- Wang Y., Xie X., and Long L.E., 2014, The effect of postharvest calcium application in hydro-cooling water on tissue calcium content, biochemical changes, and quality attributes of sweet cherry fruit, *Food Chemistry*, 160: 22-30.
<https://doi.org/10.1016/j.foodchem.2014.03.073>
- Wang Z., Yang T., Mei X., Wang N., Li X., Yang Q., Dong C., Jiang G., Lin J., Xu Y., Shen Q., Jousset A., and Banerjee S.K., 2022, Bio-organic fertilizer promotes pear yield by shaping the rhizosphere microbiome composition and functions, *Microbiology Spectrum*, 10(6): e03572-22.
<https://doi.org/10.1128/spectrum.03572-22>
- Winkler A., and Knoche M., 2019, Calcium and the physiology of sweet cherries: A review, *Scientia Horticulturae*, 245: 107-115.
<https://doi.org/10.1016/j.scienta.2018.10.012>
- Winkler A., Fiedler B., and Knoche M., 2020, Calcium physiology of sweet cherry fruits, *Trees*, 34(5): 1157-1167.
<https://doi.org/10.1007/s00468-020-01986-9>
- Wu Y., Yang X., Wang X., Yan L., Hu X., and Lian M., 2023, Effect of foliar calcium fertilization on fruit quality, cell wall enzyme activity and expression of key genes in Chinese cherry, *International Journal of Fruit Science*, 23(1): 200-216.
<https://doi.org/10.1080/15538362.2023.2265656>
- Xie Q., Xu H., Wen R., Wang L., Yang Y., Zhang H., and Su B., 2024, Integrated management of fruit trees and *Bletilla striata*: implications for soil nutrient profiles and microbial community structures, *Frontiers in Microbiology*, 15: 1307677.
<https://doi.org/10.3389/fmicb.2024.1307677>

- Xing W., Liu W., Li H., Zeng X., Fan X., Xing S., and Gong H., 2025, Development of predictive models for shelf-life of sweet cherry under different storage temperatures, *LWT*, 217: 117442.
<https://doi.org/10.1016/j.lwt.2025.117442>
- Xu H., Ediger D., and Sharifi M., 2023, Horticultural practices in early spring to mitigate the adverse effect of low temperature on fruit set in 'Lapins' sweet cherry, *Plants*, 12(3): 468.
<https://doi.org/10.3390/plants12030468>
- Zhai H., Xie P., Xie X., and Sha S.S., 2025, Deep learning-enabled hyperspectral imaging for high-accuracy non-destructive quantification of nutritional components in multi-variety apples, *Frontiers in Plant Science*, 16: 1634785.
<https://doi.org/10.3389/fpls.2025.1634785>
- Zhai Z., Feng C., Wang Y.-Y., Sun Y., Peng X., Xiao Y., Zhang X., Zhou X., Jiao J., Wang W., Du B., Wang C., Liu Y., and Li T., 2021, Genome-wide identification of the xyloglucan endotransglucosylase/hydrolase (XTH) and polygalacturonase (PG) genes and characterization of their role in fruit softening of sweet cherry, *International Journal of Molecular Sciences*, 22(22): 12331.
<https://doi.org/10.3390/ijms222212331>
- Zhang H., Zhang N., Wang L., and Li Q., 2025, Correlation analysis and comprehensive evaluation of the mineral element content of sweet cherry fruit at three developmental stages under three cultivation patterns, *International Journal of Fruit Science*, 25(1): 1-13.
<https://doi.org/10.1080/15538362.2025.2543879>
- Álvarez-Herrera J.G., Jaime-Guerrero M., and Fischer G., 2025, The effect of boron on fruit quality: A review, *Horticulturae*, 11(8): 992.
<https://doi.org/10.3390/horticulturae11080992>
- Çelik C., Karakurt Y., and Yıldırım A., 2022, Effects of hot water, calcium chloride and 1-MCP on the activity of cell wall degrading enzymes in sweet cherry (*Prunus avium*), *Harran Tarım ve Gıda Bilimleri Dergisi*, 26(4): 422-431.
<https://doi.org/10.29050/harranziraat.1168172>
- Çolak A., Çelik K., Gündeşli M.A., Gündoğdu Ö., Küçüker E., Berk S., Aglar E., and Gundogdu M., 2025, Physiological effects of MAP and calcium chloride treatments on biochemical metabolites and quality stability by reducing respiration rate in sweet cherry fruit during storage, *BMC Plant Biology*, 25(1): 1363.
<https://doi.org/10.1186/s12870-025-07454-1>

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